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MATERIALS FOR OXYGENATED WASTEWATER TREATMENT PLANT CONSTRUCTION

2-Year Progress Report

by

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One of the advanced wastewater treatment processes being considered is the introduction of high purity, molecular oxygen into the areation system of an activated sludge treatment plant. Introduction of oxygen or ozone is expected to accelerate deterioration of materials used in plant construction. The purpose of this study is to evaluate a wide range of candidate construction materials so that costly shutdowns and expensive maintenance programs can be minimized in plants using an oxygen or ozone process.

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INTRODUCTION

Increased demand on the capacity of wastewater treatment plants has led to the search for more efficient treatment processes to minimize plant size. One of the advanced wastewater treatment processes being considered is the introduction of high purity, molecular oxygen into the areation system of an activated sludge treatment plant. The oxygen reduces the required retention time thus increasing plant capacity. The use of ozone is also under consideration in hopes of achieving still greater efficiency.

Introduction of oxygen or ozone is expected to accelerate deterioration of materials used in plant construction. The purpose of this study is to evaluate a wide range of candidate construction materials so that costly shutdowns and expensive maintenance programs can be minimized in plants using an oxygen or ozone process.

Testing was accomplished by field exposure of materials samples in actual operating plants. Exposure in operating equipment is the most convincing and normally the most reliable procedure for identifying potential problem materials as well as resistant materials. In addition, the exposure conditions would be most difficult, if not impracticable, to reproduce in the laboratory.

This report covers test results after 9 months' exposure of materials at the three selected sites - Tapia Water Reclamation Plant, California; Speedway Wastewater Treatment Plant, Indianapolis, Indiana; and Westgate Wastewater Treatment Plant, Alexandria, Virginia.

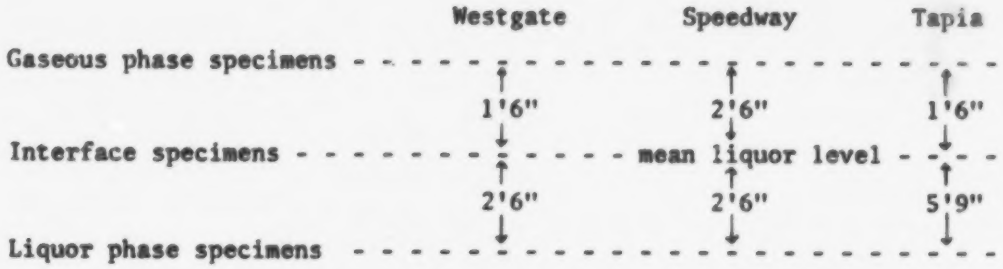
Site selection and specimen installation information was covered in the first Annual Report dated May 1973.

A TOPS diagram covering the total program is included in the Appendix. This diagram indicates the scheduled periodic inspection at the three test sites as well as the schedule for submission of reports.

TEST PROCEDURES

General

Materials evaluated in this program include protective coatings for both steel and concrete surfaces, metals and alloys, concretes, concretes as protection for reinforcing steel, rubbers, plastics, and joint sealers for concrete. Test specimens were exposed in three zones (gaseous, interface, and liquor) of the covered tanks as sketched below.



Racks for exposing the specimens at the Tapia site were fabricated of carbon steel which were then hot dipped, zinc galvanized. A typical rack is shown in Figure 1. Racks used in the Speedway and Westgate plants were constructed of stainless (Type 304) steel, Figure 2.

Concrete

Three types of portland cement concrete were exposed: Type II cement, Type V cement, and the other consisting of a Type II cement concrete which was impregnated with the monomer, methyl methacrylate, and polymerized. Mix designs for the concretes are contained in the Appendix.

Concretes were evaluated by (1) determination of compressive strength change, (2) determination of length change, and (3) visual examination for change in surface condition.

Compressive strength specimens were standard 3- by 6-inch cylinders. The length change cylinders (also 3 by 6 inches) were fitted with standard metal inserts for length measurements.

Steel Reinforcement in Concrete

Samples of concrete containing short sections of reinforcing steel were exposed to determine the effect of the test environments on the corrosion rate of the embedded steel. The reinforcing steel sections, 4 inches long by 3/4-inch diameter, were cast in 4- by 4- by 8-inch-long concrete (Type II, Type V, and polymer impregnated) prisms, providing a concrete cover of 1-5/8-inch minimum over the steel. Copper lead wires were attached to the reinforcing steel prior to concrete placement to provide electrical access.

Measurement of corrosion was accomplished by two nondestructive methods, including steel-to-electrolyte potential measurement and corrosion current determination.

Steel-to-electrolyte potential was referenced to copper-copper sulfate electrode (CSE). Magnitude of corrosion current was then determined

only on those specimens showing a high negative (more negative than minus 0.30 volt) steel-to-electrolyte potential. The potential of uncorroded steel in concrete is in the range of minus 0.10 to minus 0.30 volt to CSE. When corrosion develops, the potential drops to that of corroding steel which is in the range of about minus 0.55 volt to CSE. Determination of corrosion current was by the polarization break method, devised by Swerdtfegar of the National Bureau of Standards, described in the Appendix.

The results of these nondestructive tests will be correlated to actual corrosion of the embedded steel as determined after removal of the concrete cover at the conclusion of the test.

Metals and Alloys

1. Unstressed Specimens. - Circular coupons (2.233 inches in diameter) were exposed on standard corrosion test spools. All wrought alloy specimens were 1/16 inch thick and the coupons of cast alloys were 1/8 inch thick. Metals and alloys tested are shown in Table 1. Test spools were fabricated of Type 316 stainless steel and individual coupons were insulated from the spool and from each other through use of teflon rod insulators and teflon spacers. Duplicate specimens of each alloy were exposed. Spacing between coupons was one-half inch. The spacers also provided a crevice whereby concentration effects could be evaluated.

Average corrosion rate was computed from weight loss data, and localized corrosion was determined through pit depth measurements. Procedures for preparation of coupons for exposure and cleaning of specimens after exposure are described in the Appendix.

2. Stressed specimens. - In addition to the unstressed circular coupons, stressed specimens of the wrought metals and alloys were also prepared. The stress specimens (8 by 1/2 by 1/16 inch) were bent over a 1-inch mandrel and retained in this position to provide plastic deformation as well as high tensile stresses.

Stressed specimens are evaluated by visual examination for cracking.

Rubber and Plastic

Twelve rubber materials were selected for exposure. Duplicate sets of dumbbell-shaped, tensile specimens were cut from each material in accordance with ASTM: D 412. Holes for mounting specimens on the racks were punched one-half inch from each end of the specimens which were then looped to provide both stressed and unstressed areas.

The three flexible plastic sheeting materials were cut into duplicate 1-inch-wide, parallel edge, tensile test strips in accordance with ASTM: D 882. These specimens were not bent since stress relaxation characteristics of the flexible plastic do not make this appropriate.

The five, fabric-reinforced, flexible synthetic materials were cut into 3- by 4-inch specimens for hydrostatic pressure testing according to ASTM: D 751, Diaphragm Burst method. These specimens were also bent into a loop configuration to provide both stressed and unstressed areas.

Four rigid, fiberglass-reinforced polymers were cut into 2- by 6-inch samples for exposure. Edges of the exposed specimens were sealed with epoxy cement to reduce possible wicking in the reinforcement. A high-sulfur, rigid, natural rubber was also included with this group of materials; however, specimen edges were not sealed. Upon removal from exposure, these were bisected and edges trimmed to produce 1/2- by 6-inch specimens for flexure testing in accordance with ASTM: D 790, Method I.

High-density, polyethylene drainpipe samples were cut into 2-inch-long specimens to be tested for hoop stiffness.

Exposed materials are listed in Table 2.

The rubber and plastic materials were visually inspected at the time of removal from the exposure environment and then shipped to the laboratory for testing. In the laboratory the specimens were photographed and washed. Vapor specimens were hand dried and placed in an atmosphere of 50 percent relative humidity and 73.4° F for a minimum of 3 hours before testing. Interface and liquor specimens were immersed in fresh water after washing and maintained wet until 2 minutes (maximum) before testing.

Protective Coatings

Initially, nine coating systems were selected for exposure. However, two additional materials were introduced during the course of the test. Some of these, as appropriate, were applied to both metal (carbon steel) and concrete (cement mortar) substrates. Metal panels were 6 by 6 by 1/8 inch and the concrete panels were 6 by 6 by 1 inch. The systems applied are shown in Table 3.

Surface preparation of the steel panels was by sandblasting to white metal; whereas, the concrete specimens were lightly sandblasted and sack rubbed with a portland cement-sand grout prior to coating.

Proprietary materials identification of the coatings as well as specific application data are contained in the Appendix.

In addition to the 10 coating systems, the racks used to expose the test specimens at the Tapia plant were hot dipped, zinc galvanized to provide a test of this coating material at this site.

Joint Sealers

Three synthetic rubber, joint sealing materials were exposed, a polysulfide, a polyurethane, and a silicone, all two-component sealers conforming to the physical test requirements of Federal Specification TT-S-227. These materials were cast in a 6- by 1/2- by 1/2-inch joint formed by two concrete (cement mortar) slabs.

Two specimens of each sealer were prepared for exposure in each zone. After curing, one specimen was extended 25 percent to a joint width of 5/8 inch and the other compressed 25 percent to 3/8-inch joint width.

Evaluation was accomplished by visual observation for adhesive or cohesive failure as well as for surface degradation.

EXPOSURE CONDITIONS

Tapia Site

Samples were placed in the secondary treatment facility at the Tapia site which is a 30- by 118- by 15-foot water depth spiral-flow, aeration tank.

During this period nominal tank flow was 1 million gallons per day primary effluent plus 30 percent return activated sludge. High-purity oxygen is diffused into the mixed liquor from special submerged aeration diffusers on one side of the length of the tank.

Oxygen not dissolved or utilized in the mixed liquor is recaptured by an inflated polyvinyl-chloride tent which seals the tank. This oxygen, along with other gases, mainly carbon dioxide released by metabolism of organisms feeding on the impurities, is then recycled into the mixed liquor by an 1,800-cfm centrifugal blower. The blower feeds the original submerged aeration diffusers along the opposite side of the tank to provide the principal aeration and the spiral row agitation of the mixed liquor. The characteristics of this system during the sample exposure period are shown in Table 4.

Although the samples were installed in late October 1972, and the first examination was made in late March 1973, the tank was not in

operation for 2 months during this period. Therefore, this is referred to nominally as the 3 months' exposure. The second examination was conducted in November 1973. However, because of additional nonoperating time, the second examination is referred to as the 9 months' exposure. Because of these periods of inoperation, results from the Tapia plant would not be expected to correlate with results from the other two sites. Nevertheless the results may prove to be of value in determining the effect of plant downtime on material performance.

Speedway and Westgate Sites

Samples were placed in secondary treatment oxygen contact tanks. The Speedway plant uses the Unox system developed by the Linde Division of Union Carbide Corporation and the Westgate plant uses the Oasis system developed by Air Products and Chemicals, Inc. In both these plants, high-purity oxygen is fed into the gaseous zone between the liquor surface and the tank cover under moderate pressure (approximately 2.5 psig). A mechanical agitator with impellers at the liquor surface and at approximately one-half the liquor depth, diffuses the high-concentration oxygen atmosphere into the mixed liquor. Characteristics of these systems during the sample exposure period are shown in Table 4.

OXYGEN TEST RESULTS

Concrete

Compressive strength and length change results appear in Table 5.

1. Length change. - Results indicate that only slightly more than 10 percent of the expansion that would indicate impending failure has occured. Moreover, the rate of expansion is generally decreasing, although only slightly, for the polymer concrete.

2. Compressive strength. - Increases in the compressive strength of the Type II and V concretes indicate that curing of the specimens is continuing. A decrease in strength of the polymer concrete specimens, particularly under conditions of total immersion, has occurred. Additional exposure as planned will be required to determine the significance of this loss.

3. Surface condition. - Generally, only minor changes in surface conditions have occurred at the Tapia and Speedway sites. However, at the Westgate site, erosion of the surface was experienced as

shown in Figure 3. The most severe erosion occurred in the interface zone in the concrete fabricated of Type V cement. Less severe erosion was observed in all zones with the Type II specimens although noticeable change can be seen in the Type II vapor specimens. The polymer concrete was only slightly altered in appearance. Good compressive strength and lack of significant volume change indicates that this is a surface condition. Further exposure will be required to establish the change in the rate of erosion.

Metals and Alloys

A. Unstressed Specimens

Average corrosion rate, maximum pit depth, and crevice corrosion results for the unstressed, metal coupons appear in Table 6.

1. Aluminum alloy, AA-6061 (Figure 4), is pitting at rapid rates in all three zones at all three sites.

2. Mild carbon steel (Figure 5), low alloy steel, and austenitic gray cast iron are also pitting at excessive rates in all three zones at all three test sites.

3. Gray cast iron (Figure 6), although pitting in all three zones at two of the sites, Tapia and Speedway, is pitting only in the liquor zone at Westgate.

4. Gray cast iron, mild carbon steel, low alloy steel, austenitic gray cast iron and the aluminum alloy are pitting at the crevice.

5. The stainless steels (201, 304, 304S, 316, and 316S) and the deoxidized copper are performing well, although the copper is showing a tendency to pit in the gaseous zone at all three sites. One 304S specimen (Figure 7) exposed in the gaseous zone at Tapia was also found to be pitted to a maximum depth of 2.5 mils.

B. Stressed Specimens

Two alloys exposed in a stressed condition exhibited signs of distress after 9 months' exposure. Results are shown in Table 7.

1. One aluminum alloy, AA-6061, was found to be cracked in the liquor phase at Speedway, Figure 8.

2. One mild carbon steel sample (Figure 9) exposed at the interface at Westgate was completely fractured. However, the effect appeared to be the result of abrasive action from suspended solids activity rather than stress initiated.

Steel Reinforcement in Concrete

These results are tabulated in Table 8. The corrosion rates of steel reinforcement embedded in concrete, as determined by structure-to-electrolyte potentials as well as polarization tests, were found to be very low. The highest corrosion rate was found to be 0.036 gram per year which is so low as to be insignificant.

Rubber and Plastic Materials

A. Rubber Sheeting

Physical property tests results are shown in Table 9. The effect to date on rubber materials is discussed below by rubber type in order of increasing severity of reaction to the exposure.

1. Good performance. -

a. Ethylene Propylene Diene Monomer. - No significant change. One sample has slight elongation loss at one site in all three zones. Spotty swelling from oil splash was observed on one specimen at the Westgate site.

b. Butyl. - Very slight strength loss which appears to be stabilizing. General shrinkage trend in one sample.

2. Satisfactory performance. -

a. Neoprene. - Slight strength loss.

b. Silicone. - Slight strength and elongation loss. One specimen of each compound was broken at the interface zone at the Westgate site from mechanical damage.

c. Cholorosulfonated polyethene. - Strength loss accompanied by slight softening in all vapor phases.

3. Unsatisfactory performance. -

a. Polyacrylate. - General and continuing strength loss.

b. Nitrile-butadiene. - General strength loss with slight elongation loss. Initial ozone cracking stabilized.

c. Natural. - Strength loss, softening, distortion, initial ozone cracking, and indications of microorganism attack.

B. Plastic Sheeting

The initial stiffening of the polyvinyl-chloride sheeting experienced at the 3-month evaluation has begun to stabilize. Slight elongation losses occasionally have been accompanied by strength increases, indicating loss of plasticizer rather than attack on the polymer.

The chlorinated polyethene has shown considerable tendency to swell, although other properties have remained fairly constant except for vapor and interface strength losses at Site 3 after 9 months.

The chlorosulfonated polyethylene has shown moderate strength gain and elongation loss along with swelling. Stabilization is not yet apparent.

Physical property test results are shown in Table 10.

C. Fabric Reinforced Flexible Sheeting

No signigicant change has occurred in the butyl or ethylene propylene diene monomer materials. The chlorinated polyethylene and chlorosulfonated polyethylene materials still show considerable increase in swelling but little change in strength. One chlorinated polyethylene sample was severely abraded at the interface zone of the Westgate site. Physical property test results are shown in Table 11.

D. Rigid Polymers

No significant change from the rather wide range of original test results has occurred since the 3-month evaluation except for some stiffening in the high-sulfur hard rubber (ebonite). This follows a softening tendency found in the 3-month examination.

No change was observed in the high-density polyethylene pipe specimens during visual examination at the test site. Hoop stiffness tests will be conducted after completion of the exposure at the final examination.

Physical property test results are shown in Table 12.

Protective Coatings

Coatings test results are presented in Table 13.

A. Coatings for Metal (Steel) Surfaces

1. Good performance. - Essentially no defects or defects associated with application.

   a. System C-2, vinyl resin, Bureau of Reclamation VR-6

   b. System C-4, coal-tar epoxy, Mil-P-23236

   c. System C-9, proprietary urethane coating

2. Satisfactory performance. - Defects attributed to scoring of the coating or so few defects that coating is still serviceable.

   a. System C-1, vinyl resin, Bureau of Reclamation VR-3

   b. System C-3, American Water Works Association coal-tar enamel

   c. System C-8, proprietary phenolic coating

3. Unsatisfactory performance. -

   a. System C-5, proprietary butyl coating

   b. System C-6, proprietary butyl coating (Figure 10)

In addition, the hot-dipped zinc-galvanized coating performed poorly at the Tapia plant as indicated in the First Annual Progress Report.

B. Coatings for Concrete Surfaces

1. Good performance. -

   a. System C-9, proprietary urethane.

2. Satisfactory performance. -

   a. System C-3, American Water Works Association coal-tar enamel

   b. System C-4, coal-tar epoxy, Mil-P-23236 (Figure 11)

   c. System C-7, proprietary urethane coating

3. Unsatisfactory performance. -

   a. System C-1, vinyl resin, Bureau of Reclamation VR-3 (Figure 12)

   b. System C-5, proprietary butyl coating (Figure 13)

   c. System C-6, proprietary butyl coating

Joint Sealants

The results of sealants for concrete joints are shown in Table 14. None of the sealants exposed performed satisfactorily in all three zones at all three sites. Of the three generic types of sealants tested, the silicone performed best, failing only when continuously immersed in the liquor and under constant tensile stress. Neither the silicone nor urethane (Figure 14) materials themselves appeared to be attacked by the exposure conditions, but failed because of loss of bond of the material to the concrete substrate. The polysulfide material (Figure 15) is being degraded (softening and cracking) by the test exposure conditions.

OZONE TEST RESULTS

Adequate field sites for determining resistance of construction materials to an ozone environment have not been available. Laboratory studies were conducted in which rubber specimens identical to the materials exposed at the oxygen field sites were exposed to ozone in an atmosphere containing 50-pphm (parts per hundred million) ozone at a temperature of 38° C. Specimens were looped to provide strain as in the field sites. At the end of 8 hours' exposure, cracking was evident in the natural rubber (R-25) and the nitrile-butadiene rubber (R-34). These two specimens were completely severed from ozone attack in 7 days. In the remaining specimens, no evidence of ozone cracking could be observed with a 7X magnifying glass after 14 days, at which time the test was terminated. Further testing, in both ozone-enriched air and water, will be conducted during the next 9 months.

DISCUSSION

Concrete

The increase in compressive strength of the Types II and V concrete is to be expected as curing continues. The slightly greater strength development at the test sites compared to laboratory control cylinders

is not considered to be significant. Noticeable strength loss has occurred in the polymer concrete in the liquor phase at all three sites. However, the average strength at these three sites is approximately the same as the average strength for all polymer-concrete control cylinders immersed in tap water at the Bureau of Reclamation laboratories. Additional exposure as planned will be required before a more meaningful discussion can be made.

Metals and Alloys

A. Unstressed Specimens

The poor performance of aluminum, the gray cast iron, and the carbon steels in this test was anticipated and hence not surprising.

Aluminum alloys are rather notorious for their poor corrosion resistance, particularly in high solids waters such as wastewater, although aluminum is resistant to distilled water and deionized soft water. Aluminum derives its corrosion resistance from formation of a passive oxide film on its surface. Nearly all corrosion of aluminum results from deterioration of this passive film in localized areas resulting in pitting. This is apparently what happened to the exposed specimens. It therefore appears that the effect was not caused by the high oxygen concentration but by the water itself, as other investigators have found that aluminum-base alloys are relatively insensitive to increases in oxygen concentration.

The gray cast iron and carbon steels have been found to pit in aerated, near-neutral waters such as wastewater. Dissolved oxygen in the water reacts with hydrogen at the cathode to form other compounds. By depolarizing the cathode in this manner, corrosion is allowed to proceed.

The pitting of the austenitic gray cast iron samples in this test was unexpected. The corrosion resistance of these materials should be greater than the ordinary cast iron materials, resulting from added nickel, chromium, and copper. The effect of these additions is the formation of an austenitic, corrosion-resistant matrix. In addition, the ennobling effects of the additions render the material more passive than unalloyed versions, resulting in decreased galvanic corrosion caused by action between the graphite and matrix (graphitization) as well as when used in combination with other copper and nickel alloys. In these tests, the gray cast iron has generally performed better to date than the alloyed versions while the reverse would be normally expected. The 18-month results should provide a more definitive indication of the trend established to date.

The austenitic stainless steels are performing well as anticipated. However, the presence of incipient pitting of one sensitized 304 sample corroborates our past experiences as well as those of other investigators, in which sensitized stainless steels have been found to be susceptible to pitting. Sensitization is caused by heat treatment such as welding followed by slow cooling. The generally accepted theory is that this treatment results in chromium carbide precipitation at the grain boundaries which in turn reacts galvanically with adjacent metal devoid of chromium. This phenomenon is often referred to as intergranular corrosion.

Copper also is performing well except in the gaseous zone where the material is showning slight pitting to depths of 7.5 mils after 9 months.

Rubber and Plastics

Although relatively little change has occurred in all but three of the rubber and plastic materials being exposed, a discussion of both the changes that have occurred as well as those that have not is appropriate.

Degradation of polymeric materials is the result of the reaction of the specific service environment on each distinct polymer. It is not the purpose of this discussion to set forth the exact mechanism of deterioration of each polymer; however, some mention of these mechanisms is essential to establish an understanding of the behavior of the materials as indicated by their physical property changes. A detailed discussion would be complicated since in addition to the different reaction of each basic polymer, behavior of specific products is greatly influenced by the variety of substances which may be added to the compound, such as antioxidants, antiozonants, curing accelerators, cross linking agents, fungicides, reinforcing fillers, antibacterial agents, and extenders. For example, a material which might be a good antibacterial agent could adversely affect the oxidation rate of a polymer.

The end result of performance in terms of physical property changes has of course the greatest significance. Nevertheless, understanding some general aspects of polymer deterioration should tend to explain the material performance and provide reinforcement to the data for material selection.

The factors in the environment of this study which can be expected to influence the behavior of polymers are:

1. Oxidation (including ozone attack)

2. Biological attack

3. Water

4. Physical damage

Thermal degradation and photodegradation will not be considered to any extent because of the relatively cool operating temperatures and the absence of sunlight at the exposure sites presently in use.

1. Oxidation. - Since this study deals with oxygenated systems, it is important to know that oxygen is generally the most common factor in polymer degradation. All polymers react with oxygen at combustion temperatures and sunlight generally accelerates the process. Fortunately, with the absence of light and with the low temperatures encountered in this study (14° to 26° C), oxidation proceeds very slowly for most polymers. For example, the oxidation rate of linear polyethene at 140° C is roughly 10 times the rate at 100° C. Furthermore, at 100° C, oxygen uptake reaches a relatively early plateau. Measurement would be difficult at temperatures below 30° C since the rate of oxygen absorption is extremely slow. Even natural rubber absorbs oxygen very slowly at temperatures below 50° C.

Polymer selection is basic in reducing oxygen attack potential. Oxidation in polymers is a complicated process that involves chain reactions which result in the formation of unstable peroxy free radicals. Olefinic unsaturated hydrocarbon double bonds and other unsaturated functional groups present favorable sites for stabilization of these free radicals. Thus silicone polymers (R-32 and 532) with their silica-oxygen molecular backbone are among the most stable toward oxidative degradation. Ethylene propylene diene monomer (R-8 and 30), which has residual unsaturation only in pendent side groups and not in the main chain, is very stable as is unbranched polyethylene. Branching generally decreases oxidation resistance. Butyl rubber (R-17 and 29), having its hydrocarbon chain interrupted by a relatively few double bonds, is also quite resistant to attack. Natural rubber (R-25) with its high chemical unsaturation (presence of double bonds) is among the most suceptible of polymers to oxidation. Nevertheless, natural rubber was included in this study since it is still widely used, especially in items such as water pipe gaskets, although its percentage of the overall rubber market has decreased from 40 percent in 1969 to 22 percent in 1973.

Modification of polymer chains by addition of electrophilic side groups such as chlorine in neoprene rubber (R-5) has a protective influence on the double bond. This is generally more permanent

protection than is reliance upon antioxidants, which are used up in the performance of their function. Where oxidation rates are very low, antioxidants may provide satisfactory protection.

The effect of ozone on polymers is similar to normal oxidation in that it attacks the double bond but the process is simpler since the attack is direct. An energentic reaction occurs as a result of the electrophilic character of ozone. Scission of the double bond occurs in a reaction between the electron-deficient terminal oxygen atom of the ozone molecule and the π electrons of the double bond, ultimately resulting in the formation of polyperoxide and carbonyl compounds.

Unlike oxidation, in ozonation the thin film of the ozone reaction product (approximately 10^{-5} cm) is sufficient to restrict the access of ozone molecules to the underlying rubber if the rubber is unstrained. Therefore, unless rubber is strained (usually beyond 3 to 5 percent elongation), it appears not to have been affected by ozone and indeed suffers no significant damage. In the strained state, cracks appear which generally vary inversely in depth and directly in number to the degree of strain, with little change in the rubber between cracks.

As would be suspected the resistance of different rubber products to ozone attack is similar to their resistance to oxidation.

No unusual behavior of rubber or plastic products with regard to oxidation has been experienced to date in this study. The only attack of oxygen (O_2 or O_3) that is significant is ozone cracking in the natural rubber (R-25) and in the nitrile-butadiene rubber (R-34). These two materials are highly sensitive to ozone. In tests conducted at the Bureau of Reclamation laboratories, both materials developed cracking within 8 hours when exposed to an atmosphere of 50-pphm ozone at 38° C. Initial ozone cracking could also be observed after 12 days in the laboratory atmosphere of less than 5-pphm ozone and approximately 25° C.

It is significant that no difference in cracking was observed in any of the three zones nor was there any increase in cracking between the 3- and 9-month inspection. There was a difference in severity between sites corresponding to least delay (Tapia) and greatest delay (Westgate) in the time between stressing the specimens and installation at the sites. (It was necessary to stress the specimens prior to shipment.) Specimens of natural rubber stressed at the same time as the Westgate specimens and immersed in tap water at the Bureau of Reclamation laboratories at the same time that the Westgate specimens were installed show nearly identical severity of ozone cracking at a 9 months' inspection as the Westgate specimens, whereas specimens immersed immediately after

stressing showed no evidence of cracking. Therefore, it appears that the cracking occurred before samples were installed at the test sites and not as a result of the oxygenated wastewater environment.

The lack of substantial change in physical properties between the 3- and 9-month exposure in the natural rubber which, among polymers selected for this study, is known to be the most sensitive to oxidation and in the laboratory tests has shown extremely poor resistance to ozone, may indicate that this environment does not represent a very severe oxidation environment insofar as higher polymers are concerned. Of course, firm conclusions at this time would be premature since possible additions of antioxidants may be delaying the oxygen attack. The 18-month inspection may provide sufficient exposure time to reveal the severity of the environment to polymers; however, lack of change at this time indicates that additional exposure (beyond 18 months) may be necessary.

2. Biological attack. - Certain types of bacteria can utilize hydrocarbons, including rubber, as energy sources in their metabolism. Widespread deterioration of natural rubber water pipe joint gaskets in Europe has been reported to be the result of attack by two types of bacteria of the genus streptomyces. No deterioration of synthetic rubbers (other than polyisoprene) has been reported in Europe and no deterioration of natural rubber, widely used for pipe gaskets in the United States, has been reported. Accelerated soil burial tests conducted by the Bureau of Reclamation on several rubber products (mainly butyl and ethylene propylene diene monomer) have shown no adverse effect after 10 years' exposure. It appears that rubber compounds most resistant to oxidation and ozone attack may possibly be the most resistant to attack by microorganisms. Indeed P. B. Dickenson in the Rubber Journal (August 1965), opines that biological degradation of rubber must be preceded by an oxidation process that breaks the long hydrocarbon chain into shorter molecules which may then be consumed. In contradiction to this, some evidence of bacteria attack on the highly oxidation-resistant silicone rubbers has been reported and butyl rubber may be affected by sulfate-reducing bacteria. The polyethylene family of polymers, including chlorinated (B-6475) and chlorosulfonated polyethylene (R-18), appears to be highly resistant to microorganism attack, as is the polyvinyl-chloride resin, although plasticizers used in flexible polyvinyl chloride (B-6414) are commonly attacked with resultant stiffening of the material.

Results of our tests to date are inconclusive as to biological attack. Only one natural rubber (R-25) sample after 9 months'

exposure in the mixed liquor at the Tapia site showed some sign of localized attack. Several small circles (3 to 6 millimeters in diameter) showed discoloration and pitting accompanied by deterioration to a depth of approximately 1 millimeter. The flexible polyvinyl chloride has shown some stiffening as well as some increase in yield strength. However, the effect has been moderate and has changed little from 3 to 9 months.

Attack on polymers other than plasticized polyvinyl chloride and natural rubber is not easily determined by other than changes in physical (or electrical) properties. Testing after further exposure time will therefore be required for more definitive results.

3. Water. - Reaction of water with polymers normally would be considered secondary only to oxidation. For the present water reaction will be considered to have even less potential for deterioration than microorganism attack. The reason for this is the high availability of micoorganisms in this study and the selection of materials, except for the polyacrylate (R-27), that are resistant to water attack. However, for certain materials it may be of primary significance. For example, some studies have shown that in aerated water, immersion oxidation rates are reduced, but tests on polyethylene in aerated water at 93° C have shown as low as 1/10 the induction period as polyethene film tested at 105° C in air before change in power factor.

As in the case with oxidation, reaction of polymers with water may lead to chain scission (softening and decomposition) or to cross linking (hardening and brittleness). At present it is suspected that the embrittlement occurring in the polyacrylate (R-27) may be some form of the water attack mainly because of its poor water performance in our previous experience. The material is extremely resistant to ozone and therefore would be expected to have good oxidation resistance. There has been no evidence of surface attack of microorganisms, yet some forms of biological attack are not readily apparent on the surface. Attack of water on polymers must be preceded by permeation of the water through the bulk of the polymer. This is usually accompained by some evidence such as initial softening or swelling which has not been observed in the polyacrylate. This will be studied further as the investigation proceeds.

4. Physical damage. - A wide variety of physical abuse has been encountered by samples exposed to the three sites in this study and at least as wide a range can be expected elsewhere. The principal damage sustained so far has been tensile rupture of both silicone (R-32 and 532) specimens and a deep scratch in one reinforced chlorinated polyethylene (B-6468) and one reinforced butyl (B-6464), all at the interface of the Westgate plant.

CONCLUSIONS

1. The following materials have performed unsatisfactorily after 9 months exposure to the oxygenated wastewater environment. Therefore these materials should not be used unprotected in the construction of such wastewater plants.

   a. Aluminum alloy, AA-6061
   b. Mild carbon steel
   c. Low alloy steel
   d. Gray and austenitic cast iron
   e. Polyacrylate rubber
   f. Natural rubber
   g. Nitrile-butadiene rubber (unless modified)
   h. Vinyl resin coating (C-1) on concrete
   i. Butyl coating (C-5 and C-6)
   j. Silicone sealant continually immersed
   k. Urethane sealant
   l. Polysulfide sealant

2. Further conclusions as to materials performance cannot be made until the planned 18-month exposure is completed.

No.	Code No.	Material No.	Description	Mill	Heat No.	
1/ 1	12	-	Cast iron	-	-	
2	7	-	Mild steel	-	-	
3	7-CT	659	Cor-ten	U.S. Steel	D41534	C
4	21-201	75	Type 201SS	Jorgenson	-	≥C
5&6	18-304	656	Type 304SS	Fortuna	360792	C
7&8	19-316	657	Type 316SS	Ingersoll	41019	C
9	13-1	557	NiResist, Type I	Standard brass	13620	2
10	41-103	665	Deoxidized copper	Standard brass	-	
1/11	43-6061	-	Aluminum alloy	-	-	

1/ No analysis available.

TABLE 1

ALLOYS AND METALS - PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS

Mill	Heat No.	Chemical analysis									
		C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Cb
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
. Steel	D41534	0.10	0.42	0.10	0.019	0.35	0.11	1.06	-	0.30	-
genson	-	≥0.15	5.5-7.5	-	-	≥1.00	3.5-5.5	16.0-18.0	-	-	-
tuna	360792	0.05	1.45	0.026	0.009	0.70	9.10	18.50	-	-	-
ersoll	41019	0.07	1.55	0.018	0.003	0.64	13.15	16.03	2.40	0.13	-
ndard brass	13620	2.70	1.25	-	-	2.15	15.75	2.05	-	6.24	-
ndard brass	-	-	-	-	-	-	-	-	-	99.98	-
-	-	-	-	-	-	-	-	-	-	-	-

E 1

OPERTIES AND CHEMICAL ANALYSIS

Chemical analysis									Physical properties		
Si	Ni	Cr	Mo	Cu	Cb	Ti	B	Co	Tensile strength (psi)	Yield strength (psi)	Elongation percent in 2 inches
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
0.35	0.11	1.06	-	0.30	-	-	-	-	71,445	55,295	31
≥1.00	3.5-5.5	16.0-18.0	-	-	-	-	-	-	115,000	40,000	
0.70	9.10	18.50	-	-	-	-	-	-	93,163	49,782	
0.64	13.15	16.03	2.40	0.13	-	-	-	0.10	85,900	38,600	
2.15	15.75	2.05	-	6.24	-	-	-	-	-	-	
-	-	-	-	99.98	-	-	0.02	-	33,000	10,000	
-	-	-	-	-	-	-	-	-	-	-	

Table 2

RUBBER AND PLASTIC SPECIMENS

Rubber Sheeting

R-5	Neoprene rubber
R-8	Ethylene Propylene Diene Monomer (EPDM) rubber
R-17	Butyl rubber
R-18	Chlorosulfonated Polyethylene (CSPE) rubber
R-25	Natural rubber
R-27	Polyacrylate rubber
R-29	Butyl rubber
R-30	Ethylene Propylene Diene Monomer (EPDM) rubber
R-31	Butyl-EPDM sponge rubber blend
R-32	Silicone rubber
R-34	Nitrile Butadiene rubber
R-532	Silicone rubber

Plastic Sheeting

B-6273	Chlorosulfonated Polyethylene (CSPE) semi-cured plastic state
B-6475	Chlorinated Polyethylene (CPE)
B-6514	Polyvinyl Chloride (PVC)

Fabric Reinforced Flexible Sheeting

B-6386	Nylon reinforced CSPE
B-6399	Nylon reinforced EPDM
B-6464	Nylon reinforced Butyl
B-6467	Nylon reinforced CPE
B-6468	Polyester reinforced CPE

Rigid Polymers

RS-1	Epoxy-fiberglass laminate
RS-2	Polyester-fiberglass laminate
RS-3	Vinyl-fiberglass laminate
RS-4	Hard Natural rubber (Ebonite)
RS-5	Fiberglass reinforced plastic mortar pipe (RPM)
RS-7	High density Polyethylene (HDPE)

Table 3

PROTECTIVE COATING SYSTEMS

No.	Generic type	Specifications	Applied to Metal	Applied to Concrete
1	Vinyl resin	USBR VR-3	x	x
2	Vinyl resin	USBR VR-6	x	x
3	Coal-tar	AWWA C-203	x	x
4	Coal-tar epoxy	Mil-P-23236	x	x
5	Butyl	Proprietary	x	x
6	Butyl	Proprietary	x	x
7	Urethane	Proprietary		x
8	Phenolic	Proprietary	x	
9	Urethane	Proprietary		
10	Anodized coating	Proprietary	x[1]	
11	Hot dip zinc galvanize[2]	ASTM: A 123	x	

[1] Applied to hot-dipped, zinc-galvanized steel (ASTM: A 123).
[2] Applied to exposure racks used at the Tapia site only.

Table 4

ENVIRONMENT CHARACTERISTICS

	Normal exposure time, months	Site 1/	Atmospheric O_2 percent	Dissolved O_2 ppm	Nitrogen (ammonia) ppm	Suspended solids ppm	Volatile suspended solids ppm	Sludge volume index	pH	Total BOD ppm	Total COD ppm	Hardness ppm $CaCO_3$	Phosphate ppm	Temperature °F	Flow MGD
Minimum	3	1	32	1	0.0	2,070	1,590	117	6.4	46	60	178	12	65	
		2		1		2,750	1,870	30	7.3	35	220				3
		3	75	4	12	2,900	2,300	35	6.2	100	240	106	3	57	4
	9	1													
		2		5		2,700	1,920	32	6.9	37	190				3
		3		2	11				6.8	79	188	102	5	57	
	18	1													
		2													
		3													
Maximum	3	1	60	15	4.8	4,730	3,740	243	7.3	147	302	442	39	77	
		2		18		7,940	6,350	61	8.1	265	670				6
		3	85	14	18	5,100	3,900	67	6.7	220	460	187	13	73	10
	9	1													
		2		13		10,850	7,970	107	9.4	295	670				9
		3		15	29				7.7	265	548	198	21	79	
	18	1													
		2													
		3													
Average	3	1	44	8.4	0.6	3,738	2,693	183	6.7	84	190	275	30	68	/
		2		7.1		4,590	3,515	42	7.5	96	390				4
		3	80	8.7	14	4,100	3,300	50	6.5	160	340	130	7	64	9
	9	1	55	2.0	3	2,500	2,100	117	6.8	95	240	414	30	72	2
		2		7.4		6,310	4,974	54	7.6	108					4
		3	80	6.5	16				7.4	162	375	144	11	70	
	18	1													
		2													
		3													

/ Site 1: Tapia Water Reclamation Plant, Calabasas, California.
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana.
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia.

Table 5

CONCRETE

Concrete type			Type II					Type V					Polymer				
Exposure			Gas	Interface	Liquor	Lab. 50% RH	Lab. tap water	Gas	Interface	Liquor	Lab. 50% RH	Lab. tap water	Gas	Interface	Liquor	Lab. 50% RH	Lab. tap water
Property	Normal exposure time, months	Site 1/															
Compressive Strength psi 2/	0	4	4,730					4,620					20,900				
	3	1	6,040	5,560	5,600	4,950	5,650	5,160	4,720	4,900	5,110	5,080	17,840	18,530	18,440	22,010	20,170
		2	5/														
		3	5/														
	9	1	7,710	7,080	7,250	4,930	5,850	6,740	6,670	6,600	4,840	6,010	16,740	19,270	12,090	19,270	14,490
		2	6,220	5,780	6,540	5,000	5,950	5,820	5,860	5,660	5,000	5,530	14,950	16,760	15,380	18,370	15,670
		3	5,980	6,060	5,540	4,500	5,580	6,200	5,860	5,990	4,720	5,440	16,830	18,740	13,370	17,200	10,810
	18	1															
		2															
		3															
Length Change percent 3/	3	1	0.044	0.056	4/	-0.010	0.042	0.036	0.048	4/	-0.008	0.048	0.006	0.016	4/	-0.004	0.004
		2	0.051	0.060	0.051	0.000	0.046	0.046	0.053	0.056	0.000	0.046	0.010	0.018	0.008	0.008	0.020
		3	0.059	0.055	0.055	0.002	0.044	0.049	0.049	0.054	0.004	0.044	0.015	0.023	0.011	0.006	0.010
	9	1	0.050	0.070	0.098	0.010	0.050	0.076	0.050	0.076	-0.004	0.036	0.031	0.036	0.037	0.002	0.020
		2	0.059	0.066	0.056	-0.002	0.040	0.056	0.047	0.057	0.000	0.038	0.028	0.027	0.013	0.010	0.022
		3	0.060	0.065	0.066	-0.002	0.042	0.053	0.044	0.054	0.004	0.036	0.029	0.031	0.002	0.008	0.010
	18	1															
		2															
		3															

1/ Site 1: Tapia Water Reclamation Plant, Calabasas, California.
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana.
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia.
Site 4: USBR Laboratories, Denver, Colorado

2/ Average of duplicate specimens.
3/ Average of triplicate specimens at Site 1; duplicate specimens, Sites 2 and 3.
4/ Specimens could not be removed from exposure for measurement.
5/ Three-month specimens not exposed at Sites 2 and 3.

Code Metal or alloy Specifications			1 Gray cast iron ASTM A-48			2 Mild carbon steel AISI 1020			Low a USS
Exposure			Gas	Interface	Liquor	Gas	Interface	Liquor	Gas Inte
	Nominal exposure time, months	Site 2/							
Average Corrosion Rate 3/ mils per year	3	1	2.6	3.5	4.3	4.2	4.3	4.4	3.6
		2	3.9	0.8	4.2	6.5	0.8	3.2	3.9
		3	0.7	3.4	2.7	1.3	4.5	3.0	1.2
	9	1	2.7	1.6	2.4	5.7	2.1	2.3	4.9
		2	3.9	4.4	9.6	2.7	1.8	3.8	3.8
		3	0.7	1.7	5.2	1.4	1.4	3.7	1.2
	18	1							
		2							
		3							
Maximum Pit Depth 4/ Exposed Surface mils	3	1	7.0	3.5	4.3	9.0	5.0	6.0	11.5
		2	None	None	Incipient	10.0	9.5	7.5	18.5
		3	None	None	None	6.0	4.5	3.0	4.5
	9	1	12.0	5.0	5.0	25.0	5.0	7.0	29.0
		2	13.0	13.0	42.0	25.0	24.5	15.0	17.5
		3	None	None	16.0	6.0	12.0	6.5	5.0
	18	1							
		2							
		3							
Maximum Pit Depth 4/ Crevice 5/ mils	3	1	None	None	None	None	None	None	None
		2	None	None	Incipient	None	None	None	None
		3	None	None	None	None	None	None	None
	9	1	Incipient	Incipient	Incipient	28.0	Incipient	5.5	10.0
		2	Incipient	Incipient	6.0	6.5	5.5	12.0	7.0
		3	6.5	7.5	Incipient	11.0	11.5	Incipient	8.6
	18	1							
		2							
		3							

1/ Sensitization was accomplished by slow cooling after exposing the specimen to 1200° F

2/ Site 1: Tapia Water Reclamation Plant, Calabasas, California.
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana.
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia.

3/ Average of duplicate specimens.

4/ Maximum of duplicate specimens.

5/ Surface adjacent to teflon spacers.

Table 6

METALS AND ALLOYS - CORROSION TEST RESULTS - EPA M

el	3 Low alloy steel USS Cor-Ten			4 Stainless steel, chromium AISI 201			5 Austinitic stainless steel AISI 304			6 Sensitized, Austinitic stainless steel AISI 304 S 17		
quor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor
4.4	3.6	3.4	1.8	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
3.2	3.9	0.8	3.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
3.0	1.2	4.2	2.8	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
2.3	4.9	1.9	1.0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
3.8	3.8	2.9	6.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
3.7	1.2	1.5	2.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
6.0	11.5	3.4	5.0	None	None	None	None	None	None	None	None	None
7.5	18.5	2.5	6.0	None	None	None	None	None	None	None	None	None
3.0	4.5	3.0	5.5	None	None	None	None	None	None	None	None	None
7.0	29.0	17.0	5.0	None	None	None	None	None	None	2.5	None	None
15.0	17.5	15.0	18.0	None	None	None	None	None	None	None	None	None
6.5	5.0	3.0	12.5	None	None	None	None	None	None	None	None	None
None	None	None	None	None	None	None	None	None	None	None	None	None
None	None	None	None	None	None	None	None	None	None	None	None	None
None	None	None	None	None	None	None	None	None	None	None	None	None
5.5	10.0	Incipient	4.5	None	None	None	None	None	None	None	None	None
12.0	7.0	3.5	Incipient	None	None	None	None	None	None	None	None	None
ncipient	8.6	7.0	4.0	None	None	None	None	None	None	None	None	None

specimen to 1200° F air for 1 hour.

na.

.

Table 6

CORROSION TEST RESULTS - EPA MATERIALS STUDY

nless	6 Sensitized, Austinitic stainless steel AISI 304 S 1/			7 Austinitic stainless steel AISI 316			8 Sensitized, Austinitic stainless steel AISI 316 S 1/			9 Austinitic, gray cast iron ASTM A-436		
iquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor
<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.7	1.0	1.1
<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.3	0.9	0.5
<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	1.9	0.7
<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.9	1.6	1.4
<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.6	1.3	0.9
<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.7	1.3	0.4
None	None	None	None	None	None	None	None	None	None	2.5	3.0	1.5
None	None	None	None	None	None	None	None	None	None	10.5	12.0	7.0
None	None	None	None	None	None	None	None	None	None	3.0	Incipient	Incipient
None	2.5	None	None	None	None	None	None	None	None	8.5	5.5	10.0
None	None	None	None	None	None	None	None	None	None	11.0	12.0	8.0
None	None	None	None	None	None	None	None	None	None	7.0	5.0	7.0
None	None	None	None	None	None	None	None	None	None	None	None	Incipient
None	None	None	None	None	None	None	None	None	None	None	12.0	Incipient
None	None	None	None	None	None	None	None	None	None	None	None	Incipient
None	None	None	None	None	None	None	None	None	None	Incipient	Incipient	Incipient
None	None	None	None	None	None	None	None	None	None	6.5	Incipient	Incipient
None	None	None	None	None	None	None	None	None	None	4.0	2.0	Incipient

d, c teel 1/	9 Austinitic, gray cast iron ASTM A-436			10 Deoxidized copper ASTM B-152			11 Aluminum alloy AA-6061		
Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor
<0.1	0.7	1.0	1.1	1.2	1.5	1.3	0.3	4.7	5.1
<0.1	1.3	0.9	0.5	0.2	0.4	1.3	<0.1	<0.1	<0.1
<0.1	0.3	1.9	0.7	0.3	0.7	0.9	<0.1	<0.1	<0.1
<0.1	0.9	1.6	1.4	1.1	1.0	0.9	0.5	4.1	3.8
<0.1	1.6	1.3	0.9	0.2	0.2	2.0	0.1	<0.1	0.4
<0.1	0.7	1.3	0.4	0.3	0.3	1.0	0.1	0.4	<0.1
None	2.5	3.0	1.5	Incipient	Incipient	3.0	13.0	18.0	26.0
None	10.5	12.0	7.0	Incipient	Incipient	Incipient	None	None	10.5
None	3.0	Incipient	Incipient	Incipient	Incipient	Incipient	9.5	Incipient	Incipient
None	8.5	5.5	10.0	7.5	2.0	4.0	33.0	36.0	Perf.
None	11.0	12.0	8.0	Incipient	Incipient	Incipient	47.0	5.0	22.0
None	7.0	5.0	7.0	Incipient	Incipient	Incipient	22.0	30.0	19.0
None	None	None	Incipient	None	None	None	None	None	None
None	None	12.0	Incipient	None	None	None	None	None	None
None	None	None	Incipient	None	None	None	None	None	None
None	Incipient	Incipient	Incipient	None	None	None	Perf.	31.5	28.0
None	6.5	Incipient	Incipient	None	None	None	Incipient	None	Incipient
None	4.0	2.0	Incipient	None	None	None	11.0	6.5	7.5

Table 7

STRESSED ALLOYS

Metal or alloy		Mild carbon steel			Low alloy steel			Austinitic stainless steel			Austinitic stainless steel			Sensitized austinitic stainless steel			Austinitic stainless steel			Sensitized austinitic stainless steel			Deoxidized copper			Aluminum alloy		
Specifications		AISI 1020			USS Cor-ten			AISI 201			AISI 304			AISI 304S			AISI 316			AISI 316S			ASTM B 152			AA-6061		
Exposure[1]		G	I	L	G	I	L	G	I	L	G	I	L	G	I	L	G	I	L	G	I	L	G	I	L	G	I	L
Nominal exposure time, months	Site[2]																											
3	1		[3]			[3]			[3]			[3]			[3]			[3]			[3]			[3]			[3]	
	2	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	3	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
9[4]	1	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	2	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	[5]
	3	OK	[6]	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
18	1																											
	2																											
	3																											

[1] G - gas
I - liquor-gas interface
L - liquor

[2] 1 - Tapia
2 - Speedway
3 - Westgate

[3] Specimens not exposed at this site during this period.

[4] Six months of actual exposure at Site 1.

[5] One of the duplicate specimens cracked.

[6] One of the duplicate specimens completely fractured; wearing indicative of abrasion.

Table 8

STEEL REINFORCEMENT IN CONCRETE

Concrete type			Type II			Type V			Polymer		
Exposure			Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor
Property	Normal exposure time, months	Site 1/									
Steel-to-electrolyte potential 2/ volts	3	1	-0.11	-0.11	-0.25	-0.12	-0.08	-0.16	-0.11	-0.16	-0.11
		2	-0.54	-0.51	-0.44	-0.63	-0.50	-0.53	-0.45	-0.54	-0.36
		3	-0.49	-0.48	-0.49	-0.48	-0.46	-0.50	-0.50	-0.52	-0.52
	9	1	-0.06	-0.09	-0.05	-0.14	-0.02	-0.12	-0.39	-0.17	-0.22
		2	-0.11	-0.19	-0.36	-0.29	-0.13	-0.22	-0.22	-0.40	-0.28
		3	-0.42	-0.33	-0.41	-0.40	-0.39	-0.44	-0.32	-0.38	-0.36
	18	1									
		2									
		3									
Polarization Test Corrosion Rate grams/year x 10^{-4}	3	1	-	-	-	-	-	-	-	-	-
		2	133	277	242	215	360	270	6	124	45
		3	103	36	103	39	81	77	14	6	6
	9	1	-	-	-	-	-	-	42	-	-
		2	-	-	236	-	-	-	-	132	-
		3	100	45	97	46	95	86	10	84	96
	18	1									
		2									
		3									

1/ Site 1: Tapia Water Reclamation Plant, Calabasas, California.
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana.
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia.

2/ Steel-to-electrolyte potential as referenced to a copper-copper sulfate half cell.

Material			R-29 Butyl - G			R-17 Butyl - C			R-5 Neoprene			R-30 EPDM -	
Exposure			Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface
Property	Normal exposure time, months	Site 1/											
Tensile Strength psi	0	4	2160			1470			2400			1570	
	3	1	2175	2110	2080	1470	1515	1450	2400	2460	2485	1515	1665
		2	1940	2065	2030	1320	1260	1330	2200	2260	2260	1430	1350
		3	1910	2060	2060	1340	1260	1420	1960	2140	2160	1330	1520
	9	1	2015	2020	2010	1330	1565	1390	2155	2360	2325	1465	1665
		2	2115	1940	2105	1400	1324	1405	2360	2220	2280	1585	1710
		3	2000	1870	2090	1390	1285	1430	2065	1880	2065	1580	1435
	18	1											
		2											
		3											
		4											
Elongation Percent	0	4	625			375			290			660	
	3	1	690	655	660	405	400	365	315	310	315	670	680
		2	640	645	645	390	340	360	290	300	300	680	580
		3	640	620	655	410	320	370	300	210	295	580	600
	9	1	580	620	610	385	375	380	285	300	280	630	685
		2	630	570	640	375	365	370	300	290	265	680	605
		3	610	565	630	335	340	350	270	235	250	550	505
	18	1											
		2											
		3											
		4											
Hardness Shore "A"	0	4	64			63			73			68	
	3	1	62	63	62	64	64	66	72	71	73	65	68
		2	63	62	63	65	64	64	72	72	70	67	68
		3	58	63	63	63	63	62	71	63	68	66	73
	9	1	63	62	64	64	64	66	73	70	72	67	68
		2	63	62	61	65	64	64	72	69	68	66	66
		3	62	61	62	64	64	64	73	72	69	67	66
	18	1											
		2											
		3											
		4											
Thickness Percent Change	3	1	0.5	0.6	0.7	0.4	-0.7	-0.9	0.4	-0.2	0.0	0.2	-0.6
		2	2.0	-1.5	-1.6	-2.1	0.2	-2.3	-1.5	-2.1	-2.3	-1.9	-1.9
		3	1.3	1.3	-1.4	-0.3	-0.8	-0.8	1.1	-1.8	4.4	0.2	-3.4
	9	1	-0.3	0.8	0.5	-1.2	-1.2	-1.8	-0.8	0.3	-0.3	-0.5	0.0
		2	0.2	2.1	3.3	-1.8	-1.4	2.1	-0.8	2.4	5.8	-1.2	1.2
		3	0.2	1.5	-0.8	-2.2	-0.9	-1.9	-1.0	-0.2	2.2	-0.3	1.8
	18	1											
		2											
		3											
		4											

1/ Site 1: Tapia Water Reclamation Plant, Calabas, California
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia
Site 4: USBR Laboratories, Denver, Colorado

Table 9

RUBBER SHEETING

	R-30 EPDM - G			R-8 EPDM - C			R-32 Silicone - D			R-532 Silicone - G			R-25 Natural			
uor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas
	1570			1700			880			1100			2450			3330
485	1515	1665	1660	1740	1735	1715	970	975	450	-	-	-	1665	1930	2270	3050
260	1430	1350	1500	1480	1610	1630	830	680	820	945	1080	1105	1530	2010	1940	2540
160	1330	1520	1580	1520	1590	1610	750	480	920	810	910	865	1620	1500	1590	2310
325	1465	1665	1465	1630	1705	1635	1005	860	645	-	-	-	1575	2020	1940	2435
280	1585	1710	1595	1620	1575	1685	990	800	850	950	935	990	1570	1545	1470	2530
065	1580	1435	1525	1655	1670	1750	810	695	955	835	730	995	1630	1500	1620	2490
	660			440			180			570			615			515
315	670	680	650	475	440	425	160	160	130	-	-	-	610	625	650	540
300	680	580	650	395	410	440	155	85	125	565	620	595	600	510	610	465
295	580	600	660	420	410	430	135	45	150	430	495	430	620	590	580	430
280	630	685	630	450	420	420	155	150	105	-	-	-	560	610	615	420
265	680	605	620	400	385	425	140	140	120	480	505	520	590	565	575	445
250	550	505	545	415	410	435	95	150	120	420	400	530	560	570	565	405
	68			66			74			52			49			66
73	65	68	66	66	66	66	71	71	70	-	-	-	49	50	52	66
70	67	68	68	65	66	67	71	74	75	53	52	52	52	50	48	68
68	66	73	66	66	68	68	73	74	72	60	54	57	52	49	50	71
72	67	68	68	65	66	68	71	70	70	-	-	-	52	49	50	66
68	66	66	69	68	68	68	74	70	72	53	51	54	52	50	48	68
69	67	66	68	67	66	67	72	70	74	56	52	53	52	50	51	68
0.0	0.2	-0.6	-0.2	0.0	-1.2	-2.7	0.0	0.0	0.0	-	-	-	0.0	1.4	0.8	-0.2
2.3	-1.9	-1.9	-4.4	-0.6	0.2	-3.2	-0.3	1.6	-5.2	1.0	2.9	1.8	-2.4	6.5	0.9	-1.8
4.4	0.2	-3.4	0.3	-0.7	-0.2	-0.8	-1.3	-0.3	-1.1	1.4	1.7	5.2	0.2	0.2	2.8	0.0
0.3	-0.5	0.0	-1.2	-0.6	-1.4	-3.3	-1.0	-0.7	-0.8	-	-	-	-0.8	0.2	0.2	-0.6
5.8	-1.2	1.2	1.8	-2.8	-1.9	0.1	-0.6	0.2	2.0	-0.3	2.9	1.6	0.5	4.1	3.5	-0.2
2.2	-0.3	1.8	0.3	-0.3	3.5	-0.2	-0.4	-0.4	1.0	-0.3	1.0	0.6	-0.8	1.3	0.0	-0.7

	R-25 Natuyal			R-34 NBR			R-27 Polyacrylate			R-18 CSPE			R-31 EPDM/Butyl		
Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor
	2450			3330			2030			1520			145		
-	1665	1930	2270	3050	2865	3000	2150	1090	1770	1315	1565	1525	140	145	170
1105	1530	2010	1940	2540	2590	2850	1350	1770	1690	1280	1350	1340	135	120	150
865	1620	1500	1590	2310	2380	2400	1020	1070	1890	1330	1400	1611	150	120	145
-	1575	2020	1940	2435	2670	2870	1320	985	1255	1215	1755	1520	140	155	155
990	1570	1545	1470	2530	2605	2690	1730	1175	1200	1335	1645	1635	140	130	150
995	1630	1500	1620	2490	2345	2465	1295	1790	1210	1230	1785	1465	120	155	140
	615			515			125			465			200		
-	610	625	650	540	620	500	135	95	110	475	470	440	215	245	245
595	600	510	610	465	460	470	105	135	120	460	400	410	200	210	250
430	620	590	580	430	430	430	105	100	160	455	425	450	235	240	230
-	560	610	615	420	480	530	80	70	110	350	340	400	235	265	260
520	590	565	575	445	445	440	130	110	105	430	390	370	280	265	220
530	560	570	565	405	400	400	90	110	110	315	410	400	205	290	245
	49			66			74			68			-		
-	49	50	52	66	66	64	70	71	70	68	66	64	-	-	-
52	52	50	48	68	67	68	72	72	72	69	68	68	-	-	-
57	52	49	50	71	66	67	67	71	71	67	66	67	-	-	-
-	52	49	50	66	66	67	74	72	72	74	69	68	-	-	-
54	52	50	48	68	68	68	72	72	73	70	68	68	-	-	-
53	52	50	51	68	67	68	71	70	71	72	68	67	-	-	-
-	0.0	1.4	0.8	-0.2	0.3	0.7	1.9	2.1	1.3	0.0	1.5	1.6	5.0	-18.2	-20.6
1.8	-2.4	6.5	0.9	-1.8	-6.0	1.6	-8.3	-4.4	-3.0	-0.6	1.3	1.5	-1.7	-8.0	-1.5
5.2	0.2	0.2	2.8	0.0	-0.2	0.4	-1.9	-2.2	-3.2	0.7	0.2	3.1	-6.6	-16.2	-12.0
-	-0.8	0.2	0.2	-0.6	-0.3	-0.4	0.0	0.4	1.6	0.0	1.2	0.7	-5.7	-13.5	-14.9
1.6	0.5	4.1	3.5	-0.2	0.4	0.5	0.3	0.2	0.8	0.2	2.3	3.2	-9.0	-8.0	-1.0
0.6	-0.8	1.3	0.0	-0.7	-0.2	-2.6	-2.7	-3.0	0.8	-0.8	0.3		-10.0	-31.0	-13.5

Table 10

PLASTIC SHEETING

Material			B-6414 PVC			B-6273 CSPE			B-6475 CPE		
Exposure			Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor
Property	Normal exposure time, months	Site 1/									
Tensile Strength psi	0	4	3,130			1,820			1,990		
	3	1	2,700	3,185	3,140	1,800	2,110	1,950	2.020	2,160	1,940
		2	2,295	-	2,835	1,585	1,955	2,090	1 965	1,762	2,145
		3	3,110	3,030	3,075	2,000	2,280	2,375	2,010	1,910	1,994
	9	1	3,300	3,620	3,440	2,070	2,295	2,160	2,085	2,080	2,040
		2	3,180	2,840	2,715	2,125	2,620	2,195	1,870	1,720	1,960
		3	3,005	2,930	3,050	2,655	2,575	2,525	1,445	1,305	1,930
	18	1									
		2									
		3									
		4									
Elongation Percent	0	4	300			215			300		
	3	1	265	330	290	230	245	265	340	330	310
		2	220	-	270	260	185	220	350	265	300
		3	270	250	325	205	210	220	320	300	295
	9	1	235	285	270	225	215	245	280	295	300
		2	230	220	170	190	180	200	270	215	290
		3	240	255	290	155	190	140	300	260	265
	18	1									
		2									
		3									
		4									
Thickness Percent Change	3	1	3.0	0.0	-4.0	1.5	2.1	1.7	6.2	11.8	7.5
		2	-1.4	-1.9	-1.4	-2.5	-1.8	-4.9	4.1	4.3	2.6
		3	-3.5	-1.0	-2.0	1.1	4.5	4.5	7.8	4.5	11.7
	9	1	-5.0	-6.1	-6.5	1.5	4.4	2.6	4.8	10.5	8.6
		2	-3.9	-1.0	-1.0	3.5	7.0	4.2	5.3	14.2	9.7
		3	0	-1.0	0	2.4	1.8	2.2	3.0	4.1	5.4
	18	1									
		2									
		3									
		4									

1/ Site 1: Tapia Water Reclamation Plant, Calabasas, California.
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana.
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia.
Site 4: USBR Laboratories, Denver, Colorado.

Table 11

FABRIC REINFORCED FLEXIBLE SHEETING

Material			B-6464 Butyl Nylon reinforced			B-6399 EPDM Nylon reinforced			B-6467 CPE Nylon reinforced			B-6468 CPE Polyester reinforced			B-6386 CSPE Nylon reinforced		
Exposure			Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor
Property	Normal exposure time, months	Site 1/															
Burst strength psi	0	4	215			180			505			415			125		
	3	1	210	200	200	165	150	150	470	460	455	340	370	340	-	-	115
		2	200	205	205	170	160	160	440	445	445	385	380	380	-	-	120
		3	205	210	200	165	160	155	470	470	470	350	355	340	-	-	110
	9	1	220	200	210	185	165	165	405	485	485	410	350	370	-	-	-
		2	210	205	205	150	150	150	440	455	460	360	360	370	-	-	135
		3	205	200	210	140	150	160	390	465	480	345	385	360	-	-	155
	18	1															
		2															
		3															
		4															
Thickness percent change	3	1	-0.4	-0.3	0.3	0.6	0.1	0.4	5.9	8.4	7.1	9.2	11.3	11.3	-	-	5.3
		2	-1.7	-0.5	1.3	0.0	-0.9	0.4	4.5	2.0	2.8	7.6	6.3	6.6	-	-	8.5
		3	1.1	0.7	0.4	-0.8	1.5	3.7	5.5	6.1	7.2	9.4	7.4	11.5	-	-	10.0
	9	1	-0.8	0.2	0.0	-0.2	0.9	-2.0	1.3	11.1	11.8	13.4	20.3	20.0	-	-	-
		2	0.2	2.5	-0.1	-2.1	2.0	3.6	9.9	11.8	7.5	13.2	16.3	17.5	-	-	14.9
		3	-0.2	4.2	1.2	-0.2	-1.6	1.4	8.6	10.5	10.9	13.3	18.0	18.6	-	-	10.6
	18	1															
		2															
		3															
		4															

1/ Site 1: Tapia Water Reclamation Plant, Calabasas, California.
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana.
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia.
Site 4: USBR Laboratories, Denver, Colorado.

Table 12

RIGID POLYMERS

Material			RS-1 Epoxy			RS-2 Polyester			RS-3 Vinyl			RS-4 Hard Rubber			RS-5 RFX		
Exposure			Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor	Gas	Interface	Liquor
Property	Normal exposure time, months	Site 1/															
Flexural Strength psi	0	4	15,710			24,530			21,050			1,770			10,350		
	3	1	14,180	18,870	15,430	28,190	22,260	25,270	24,730	24,120	19,220	865	-	753	8,430	9,990	10,400
		2	17,490	16,720	16,070	19,450	20,690	20,550	13,610	17,840	14,660	-	-	810	7,598	6,590	6,970
		3	13,680	16,660	14,690	22,350	27,440	22,750	17,890	17,700	20,270	-	-	836	8,900	9,660	7,846
	9	1	16,200	15,660	17,900	25,780	24,170	25,880	16,240	13,930	19,340	-	-	-	10,790	11,710	14,110
		2	18,960	18,900	16,560	20,300	20,750	21,230	19,260	17,260	17,690	-	-	1,195	13,130	13,360	14,000
		3	17,290	16,470	14,950	25,270	23,870	19,680	16,780	16,680	16,350	-	-	1,234	14,090	10,550	11,960
	18	1															
		2															
		3															
		4															
Maximum Strain percent	0	4	2.40			2.20			2.20			2.39			1.59		
	3	1	1.70	2.12	1.85	2.84	2.84	3.20	2.42	2.97	2.39	7.80	-	14.90	1.41	1.48	1.72
		2	1.90	1.68	1.71	2.27	2.47	2.29	1.46	2.24	1.98	-	-	18.40	1.56	1.20	1.20
		3	1.62	1.83	1.83	2.81	3.21	2.73	2.28	2.15	2.37	-	-	10.80	1.71	1.99	1.64
	9	1	1.94	1.84	2.20	2.58	3.17	2.92	1.75	1.54	2.20	-	-	-	1.67	1.83	2.10
		2	2.39	2.26	1.92	2.61	2.40	2.42	2.04	2.02	2.00	-	-	5.67	1.85	2.01	1.56
		3	2.35	1.88	1.86	2.58	2.68	2.48	1.88	1.77	1.86	-		5.94	2.02	1.72	2.07
	18	1															
		2															
		3															
		4															

1/ Site 1: Tapia Water Reclamation Plant, Calabasas, California.
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana.
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia.
Site 4: USBR Laboratories, Denver, Colorado.

Table 13

PROTECTIVE COATING SYSTEMS

Coating	Exposure Substrate: Nominal exposure time, months	Site 1/	Gas: Steel	Gas: Concrete	Water: Steel
C-1 Vinyl Resin-3	3	1	- -	- -	- -
		2	Blisters at score	OK	OK
		3	Blisters at score	OK	Blisters at score
	9	1 2/	OK	OK	OK
		2	Pinhead blisters around score	OK	Slight blistering around score
		3	Pinhead blisters around score	Pinhead blisters, both sides	Slight blistering around score
	18	2			
		3			
		4			
C-2 Vinyl Resin-6	3	1	- -	3/	- -
		2	OK		OK
		3	OK		OK
	9	1 2/	OK		OK
		2	OK		Slight pinhead blistering, OK
		3	OK		OK
	18	2			
		3			
		4			
C-3 Coal Tar Enamel	3	1	- -	- -	- -
		2	OK	OK	OK
		3	OK	OK	Embrittlement
	9	1 2/	Two corners impacted	Craters on scored side	One corner chipped
		2	OK	Craters	Cracking, both sides
		3	Slight cracking, both sides	Slight cracking, both sides	Alligator cracking, both sides
	18	2			
		3			
		4			
C-4 Coal Tar Epoxy	3	1	- -	- -	- -
		2	OK	OK	OK
		3	OK	OK	OK
	9	1 2/	Thin area on edge with corrosion	Slight pinhead blistering on scored side	OK
		2	OK	OK	OK
		3	Slight pinhead blistering, OK	Slight pinhead blistering, both sides	OK
	18	2			
		3			
		4			
C-5 Acryl (E)	3	1	- -	- -	- -
		2	Blisters at score	OK	Erosion
		3	Blisters at score	OK	Erosion
	9	1 2/	Corrosion, unscribed side, 1 percent	OK	Pinhead blisters at score
		2	OK	Pinhead blistering around score and backside	Pinhead blisters at score
		3	Pinhead blisters, both sides	Severe pinhead blisters, both sides	Pinhead blisters, both sides
	18	2			
		3			
		4			
C-6 Acryl Lac	3	1	- -	- -	- -
		2	OK	OK	OK
		3	OK	OK	Erosion
	9	1 2/	Corrosion on edge	Impacted area, unscored side	OK
		2	Pinhead blisters at score and on backside	Severe blistering, both sides	OK
		3	Pinhead blisters at score and on backside	Pinhead blistering, both sides	Pinhead blisters at score
	18	2			
		3			
		4			
C-7 Urethane Coal Tar	3	1		- -	
		2	3/	OK	3/
		3		OK	
	9	1 2/		Few craters, OK	
		2			
		3		OK	
	18	2		Craters, OK	
		3			
		4			
C-8 Phenolic	3	1	- -	3/	- -
		2	OK		OK
		3	Rust at score		Rust at score
	9	1 2/	One impacted area with rust		One impacted area
		2	OK		OK
		3	Chipped area around center hole		Slight cracking due to scoring
	18	2			
		3			
		4			
C-9 Urethane (Clear)	3	1	- -	No specimen exposed	- -
		2	OK	OK	OK
		3	OK	OK	OK
	9	1 2/	OK	No specimen exposed	OK
		2	OK	OK	OK
		3	OK	OK	OK
	18	2			
		3			
		4			
C-10	9	2			
		3			
		4			

1/ Site 1: Tapia Water Reclamation Plant, Calabasas, California; Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana; Site 3: Westgate Wastewater
2/ Exposure at Site 1 was 6 months.
3/ Coating not tested on this substrate.

Table 13

PROTECTIVE COATING SYSTEMS

Gas		Interface		Liquor	
	Concrete	Steel	Concrete	Steel	Concrete
	- - OK OK	- - OK Blisters at score	- - OK OK	- - Rust at score OK	- - OK OK
around score ground score	OK OK Pinhead blisters, both sides	OK Slight blistering around score Slight blistering around score	100 percent pinhead blistering Pinhead blisters, both sides Pinhead blisters, both sides	Slight pinhead blistering at score OK Slight pinhead blisters at score	100 percent pinhead blistering OK Pinhead blisters, both sides
	1/	- - OK OK	1/	- - Rust at score OK	1/
		OK Slight pinhead blistering, OK OK		OK OK OK	
	- - OK OK	- - OK Embrittlement	- - OK Embrittlement	- - Mechanical damage Mechanical damage	- - Mechanical damage Mechanical damage
ted both sides	Craters on scored side Craters Slight cracking, both sides	One corner chipped Cracking, both sides Alligator cracking, both sides	Craters on scored side Cracking, both sides Alligator cracking, both sides	OK One corner chipped OK	Craters on scored side Slight cratering OK
	- - OK OK	- - OK OK	- - OK OK	- - OK OK	- - OK OK
with corrosion listering, OK	Slight pinhead blistering on scored side OK Slight pinhead blistering, both sides	OK OK OK	Pinhead blistering, both sides OK OK	OK OK Slight pinhead blistering, OK	Pinhead blistering both sides OK Pinhead blistering, scored side
	- - OK OK	- - Erosion Erosion	- - Erosion Erosion	- - OK Erosion	- - General blistering Erosion
hbed side, 1 percent both sides	OK Pinhead blistering around score and backside Severe pinhead blisters, both sides	Pinhead blisters at score Pinhead blisters at score Pinhead blisters, both sides	100 percent blistering and flaking Small pinhead blisters, both sides Severe pinhead blisters, both sides	100 percent pinpoint blistering Large blisters at score Pinhead blisters at score	100 percent blistering & flaking Severe blistering, both sides Pinhead blisters, both sides
	- - OK OK	- - OK Erosion	- - OK Erosion	- - OK Erosion	- - OK Erosion
at score and on backside at score and on backside	Impacted area, unscored side Severe blistering, both sides Pinhead blistering, both sides	OK OK Pinhead blisters at score	100 percent pinhead blistering Severe blistering, both sides Pinhead blisters, both sides	One impacted area Pinhead blistering along score OK	100 percent pinhead blistering Large blisters along score Pinhead blisters at score
	- - OK OK	1/	- - OK OK	1/	- - OK OK
	Few craters, OK OK Craters, OK		Slight cratering, both sides; large blisters Few craters, OK Few craters, OK		Large pinhead blisters, cratering Few craters, OK Few craters, OK
	1/	- - OK Rust at score	1/	- - OK OK	1/
with rust center hole		One impacted area OK Slight cracking due to scoring		Two impacted areas OK Chipped area around center hole	
	No specimen exposed OK OK	- - OK OK	No specimen exposed OK OK	- - OK OK	No specimen exposed OK OK
	No specimen exposed OK OK	OK OK OK	No specimen exposed OK OK	OK OK OK	No specimen exposed OK OK

California; Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana; Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia; Site 4: USBR Laboratories, Denver, Colorado.

Exposure			Gas	
			Tension	Co
Sealant	Normal exposure time, months	Site 1/		
Silicone	3	1	OK	OK
		2	OK	OK
		3	Bond failure	OK
	9	1	OK	OK
		2	OK	OK
		3	100 percent bond failure	OK
	18	1		
		2		
		3		
Urethane	3	1	OK	OK
		2	Bond failure	OK
		3	Bond failure	OK
	9	1	OK	OK
		2	100 percent bond failure	OK
		3	100 percent bond failure	OK
	18	1		
		2		
		3		
Polysulfide	3	1	OK	OK
		2	OK	OK
		3	Surface degradation	Surface degra
	9	1	Surface cracking	Surface crack
		2	1/10-inch-thick surface degradation	1/10-inch-thi
		3	Severe cracking and softening	Softening
	18	1		
		2		
		3		

1/ Site 1: Tapia Water Reclamation Plant, Calabasas, California
Site 2: Speedway Wastewater Treatment Plant, Indianapolis, Indiana
Site 3: Westgate Wastewater Treatment Plant, Alexandria, Virginia

Table 14

JOINT SEALANTS

Gas		Interface	
	Compression	Tension	Compression
	OK OK OK	OK OK Bond failure	OK OK OK
	OK OK OK	OK OK 100 percent bond failure	OK OK OK
	OK OK OK	OK Bond failure Bond failure	OK OK OK
	OK OK OK	75 percent bond failure 100 percent bond failure 100 percent bond failure	OK OK OK
	OK OK Surface degradation	OK OK Slight surface degradation	OK OK Slight surface degradation
tion	Surface cracking 1/10-inch-thick surface degradation Softening	Surface cracking 1/8-inch-thick surface degradation Softening	Surface cracking 1/8-inch-thick surface degr Softening

ana
ia

	Liquor	
Compression	Tension	Compression
	OK	OK
	OK	OK
	25 percent bond failure	OK
	OK	OK
	OK	OK
	50 percent bond failure	OK
	OK	OK
	Bond failure	OK
	Bond failure	OK
	80 percent bond failure	OK
	100 percent bond failure	OK
	100 percent cohesion failure	OK
	OK	OK
	OK	OK
face degradation	Surface degradation	Surface degradation
acking	Surface cracking	Surface cracking
hick surface degradation	1/32-inch-thick surface degradation	1/16-inch-thick surface degradation
	Slight softening	Slight softening

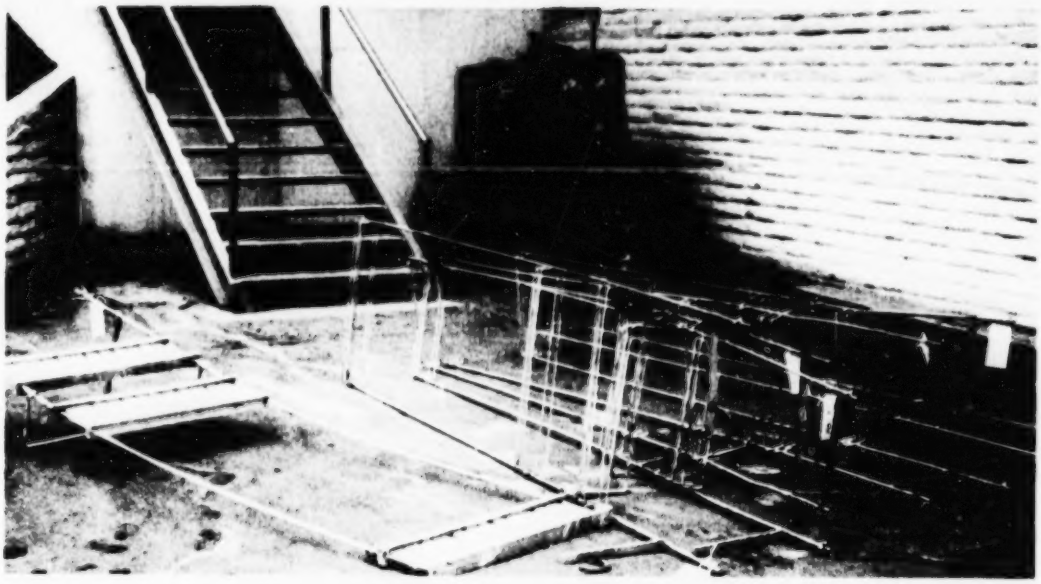


Figure 1. Typical rack used to expose test specimens at the Tapia plant. Photo P801-D-74646

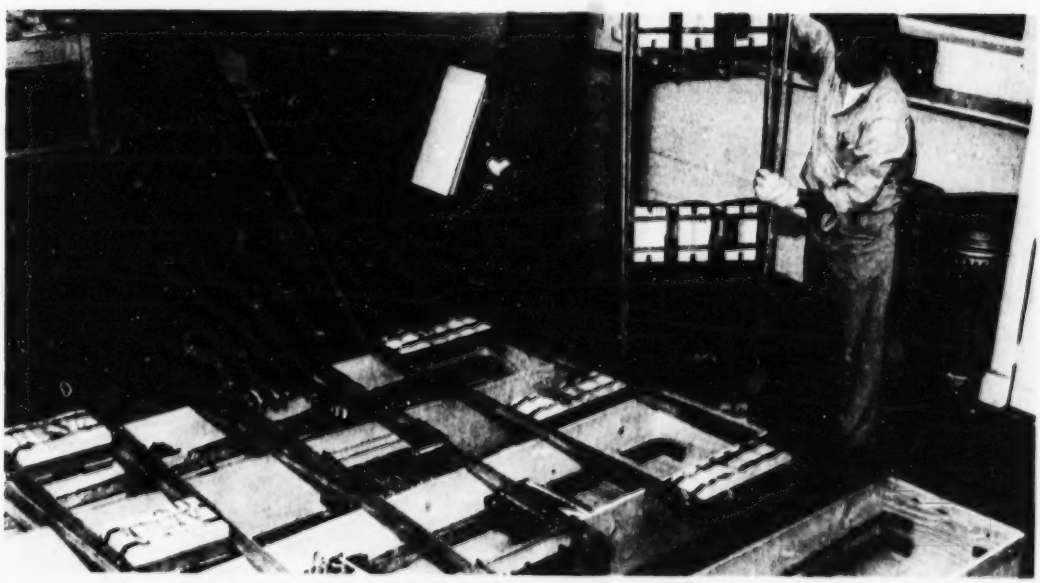
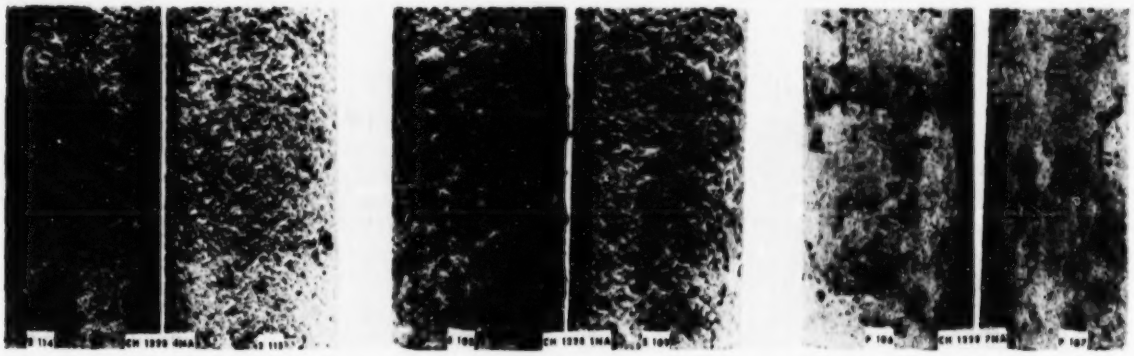
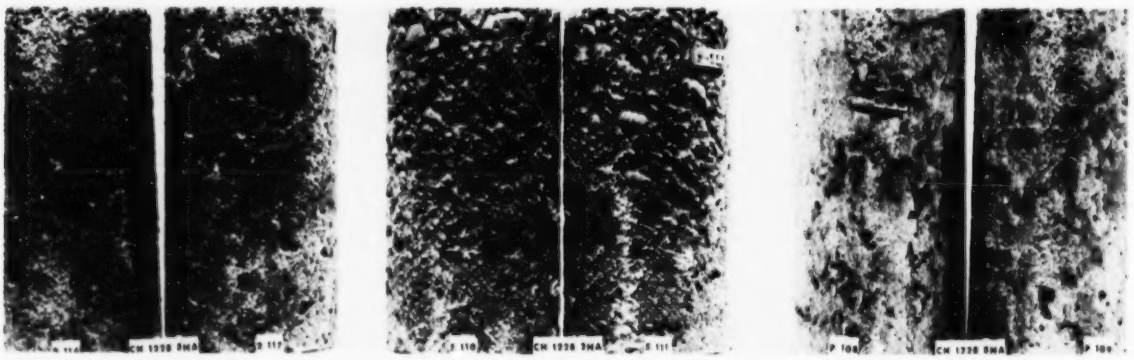


Figure 2. Racks for supporting test specimen at the Speedway plant. Similar but shorter racks were used at the Westgate plant. Photo P801-D-74647



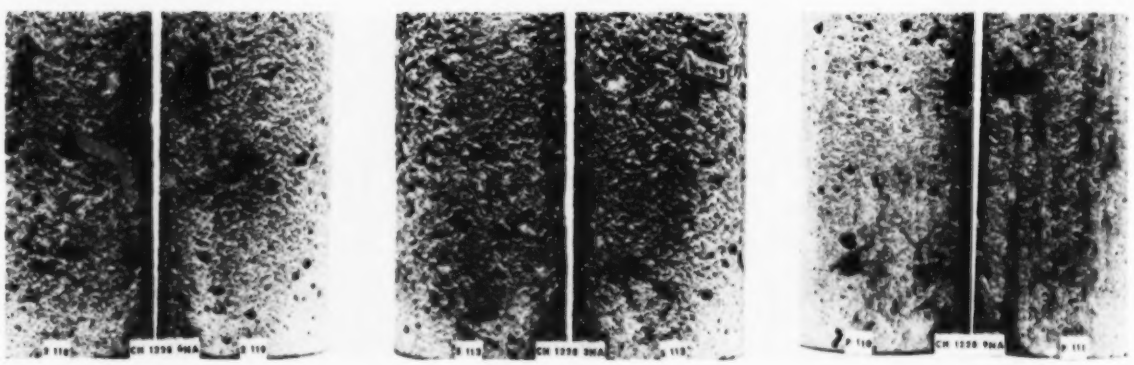
Type II | Type V | Polymer concrete

VAPOR EXPOSURE



Type II | Type V | Polymer concrete

INTERFACE EXPOSURE



Type II | Type V | Polymer concrete

LIQUOR EXPOSURE

Figure 3. Surface conditions of concrete specimens exposed at the Westgate Plant (9 months). Photo P801-D-74660

Figure 4. Aluminum alloy exposed for 9 months in the liquor at the Tapia plant. Note severe pitting and perforation (right). Photo P801-D-74648

Figure 5. Elongated pits on mild carbon steel coupon after 9 months exposure in the vapor phase at the Speedway plant. Photo P801-D-74649

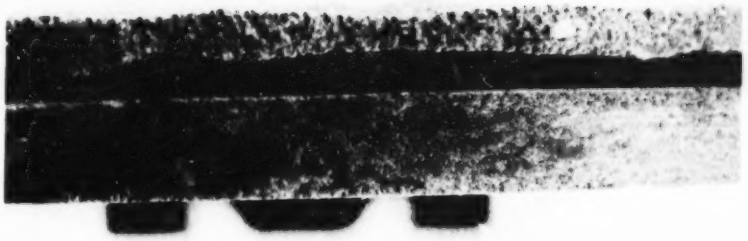


Figure 6. Edge view of exposed (top) and unexposed coupons of cast iron. Upper sample was continuously immersed for 9 months in the liquor at the Speedway plant. Thickness caused by graphitization was 70 percent. Photo P801-D-74650

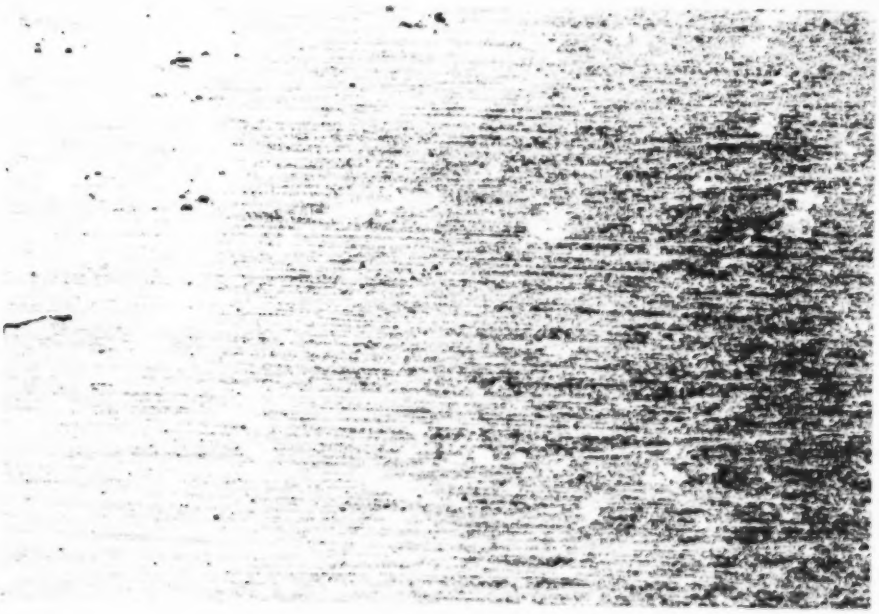


Figure 7. 20X magnification of sensitized 304 stainless steel coupon exposed for 9 months at the vapor zone at Tapia. Note pitting caused by intergranular corrosion. Photo P801-D-74651

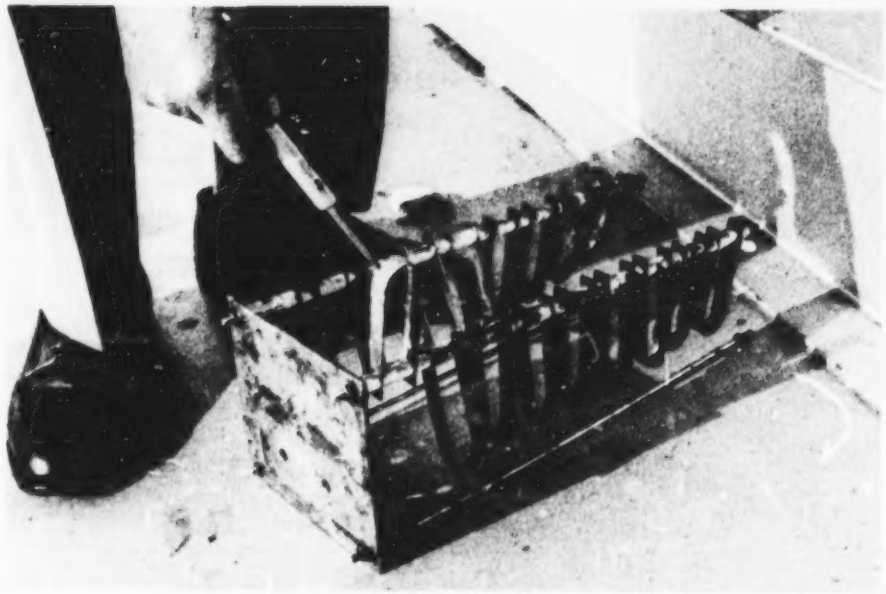


Figure 8. Crack in stressed aluminum sample (AA-6061) after 9 months continuous immersion in the liquor at the Speedway plant. Duplicate specimen was found to be intact. Photo P801-D-74656

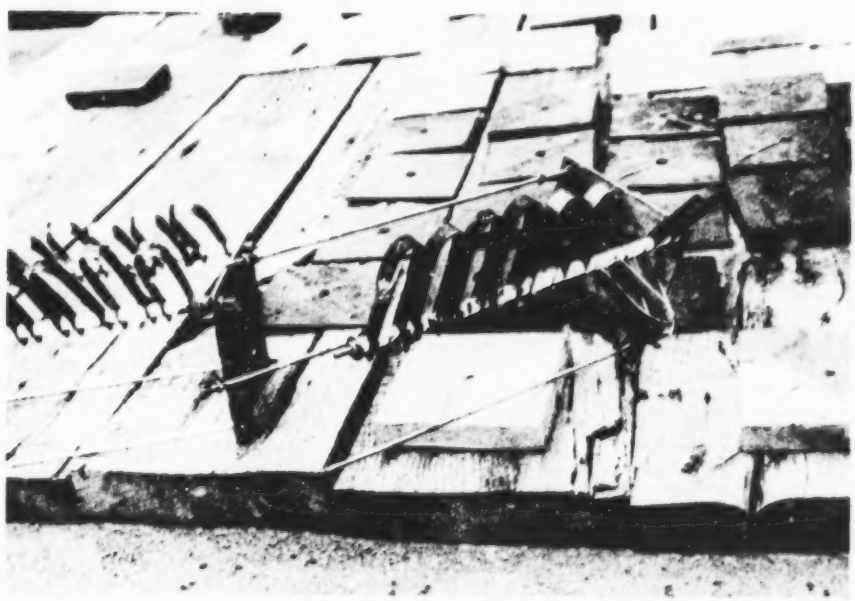


Figure 9. Stressed metal and alloy samples and coatings samples at the Westgate plant. Note sample, mild carbon steel, completely fractured. Effect is believed to be caused by abrasive action of the suspended solids on this sample which was located at the interface. Photo P801-D-74657

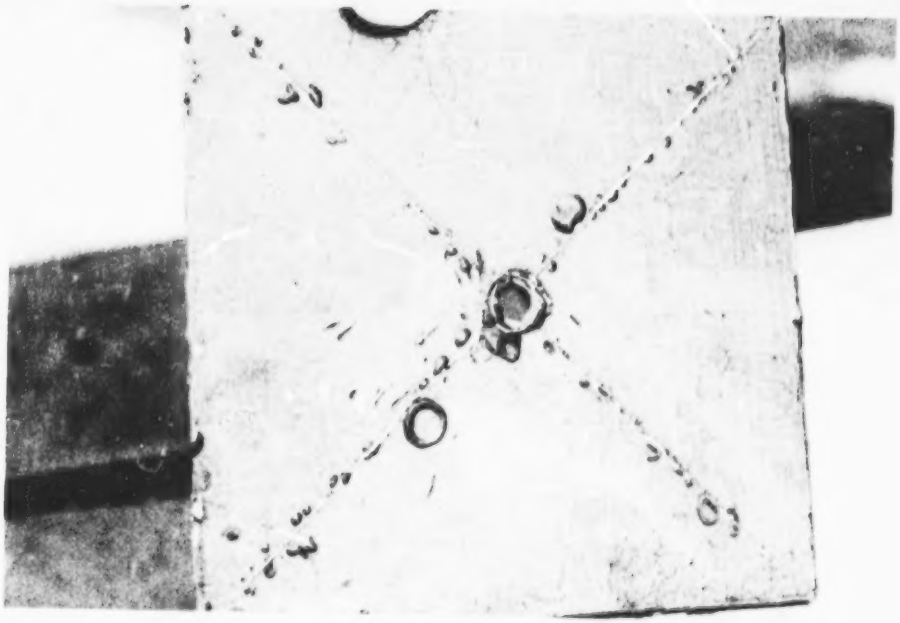


Figure 10. Proprietary butyl rubber coating (No. C6) on steel panel after 6 months continuous immersion in the liquor at the Tapia Plant. Photo P801-D-74652

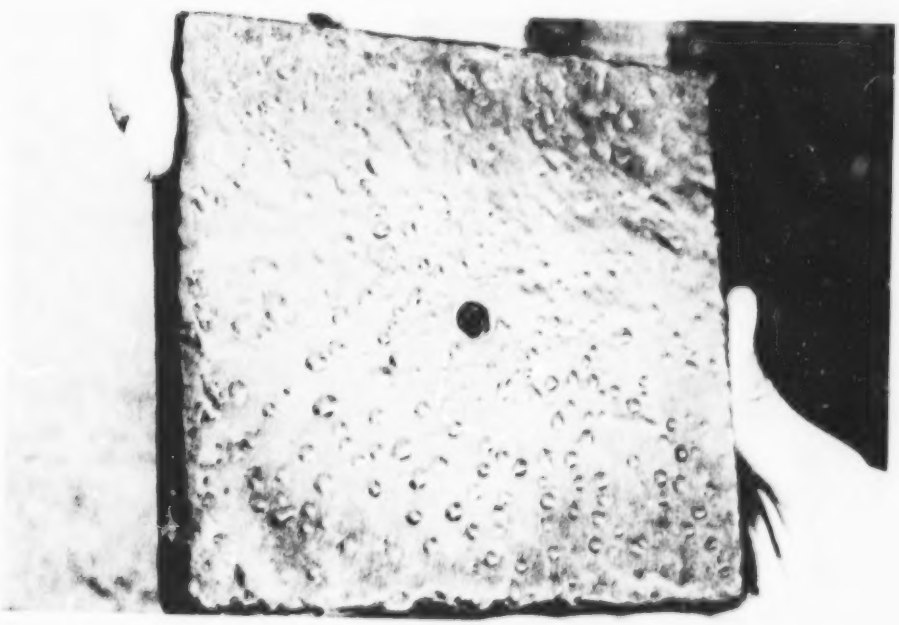


Figure 11. Coal-tar epoxy coating system on concrete panel after 6 months immersion in the liquor at the Tapia plant. Photo P801-D-74653

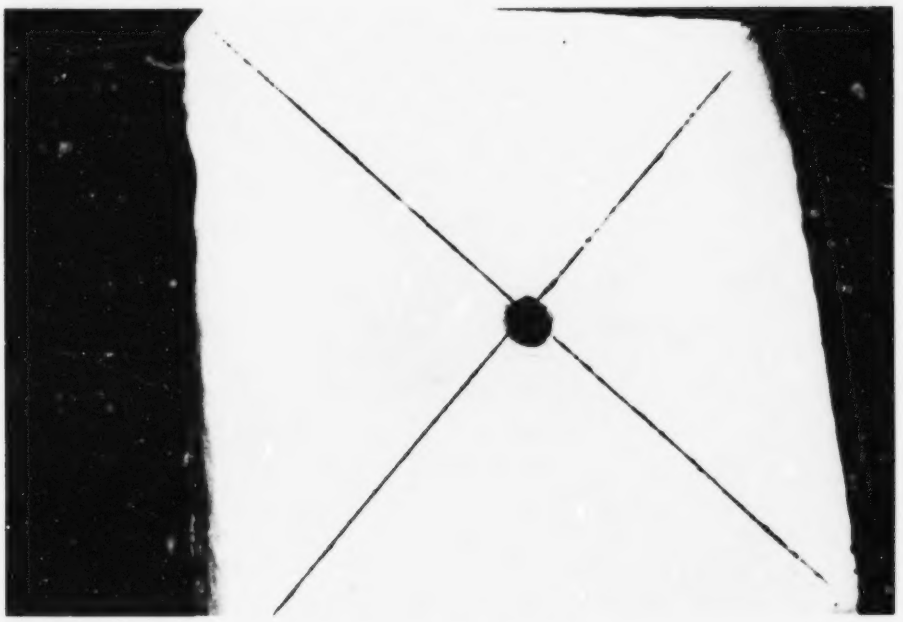


Figure 12. Bureau of Reclamation Specifications VR-3 coating system on concrete panel after 6 months immersion in the liquor at the Tapia plant. Note blistering. Photo P801-D-74654

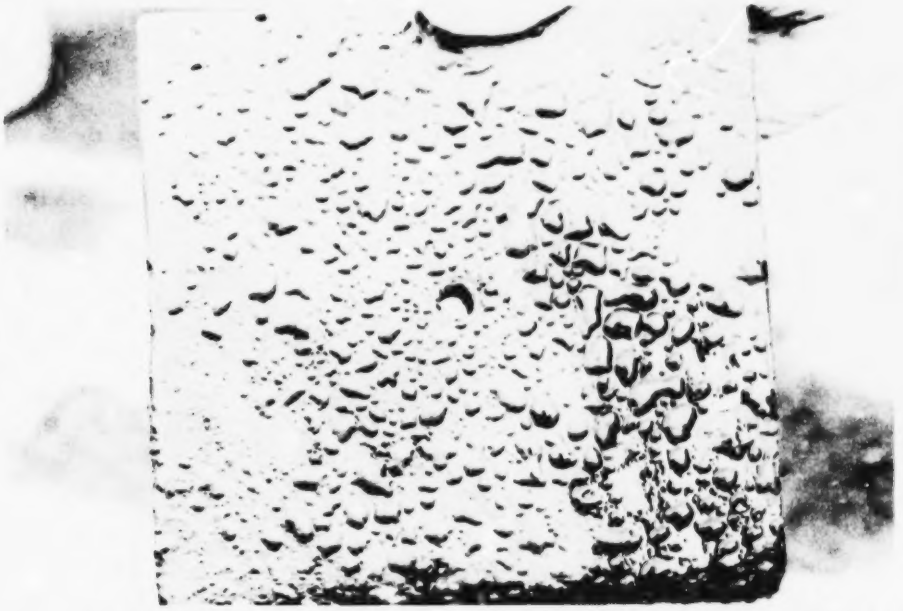


Figure 13. Proprietary butyl rubber coating (No. C5) on concrete panel after 6 months continuous immersion in the liquor at the Tapia plant. Photo P801-D-74655

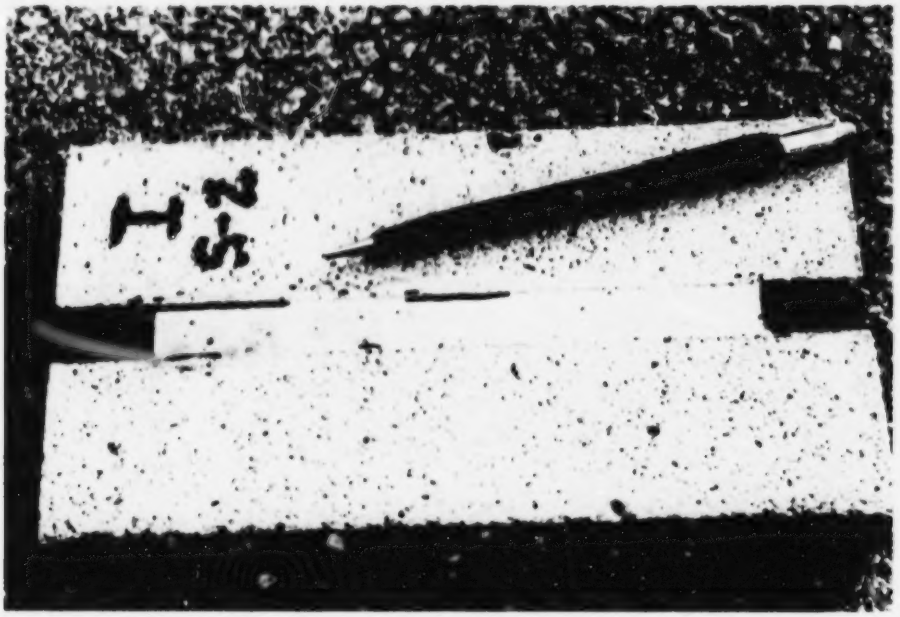


Figure 14. Bond failure of polyurethane joint sealing material after 9 months of continuous extension of 125 percent of initial width at the interface of the Tapia plant. Photo P801-D-74658

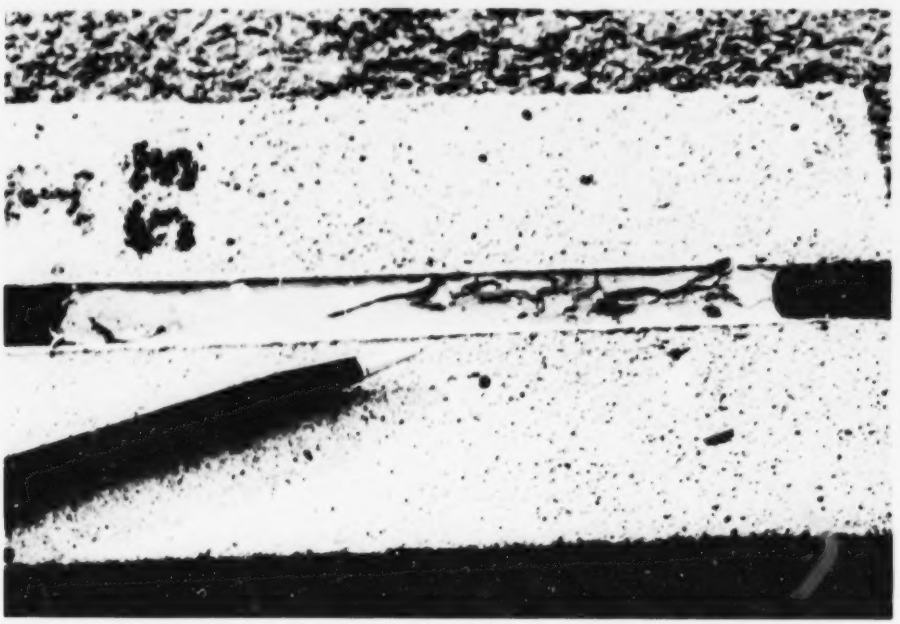


Figure 15. Surface deterioration of polysulfide joint sealing material after 9 months exposure at the interface of the Tapia plant. Photo P801-D-74659

List of Materials Under Test

Concrete

Type II, Type V, Polymer impregnated Type II.

Steel Reinforcement in Concrete

Reinforcing steel embedded in Type II, V, and Polymer concrete.

Metals and Alloys

Grey cast iron; austenitic grey cast; mild carbon steel low alloy steel; Types 201, 304 and 316 stainless steel copper; and AA-6061 Aluminum.

Rubber and Plastic

Neoprene, Butyl, Natural rubber, Ethylene Propylene Diene Monomer Polyacrylate, Silicone, Nitrile Butadiene, Chlorinated Polyethylene, Chlorosulfonated Polyethene, Polyvinyl Chloride, Epoxy-fiberglass, Polyester-fiberglass, Vinyl-fiberglass, Reinforced plastic mortar pipe.

Protective Coatings

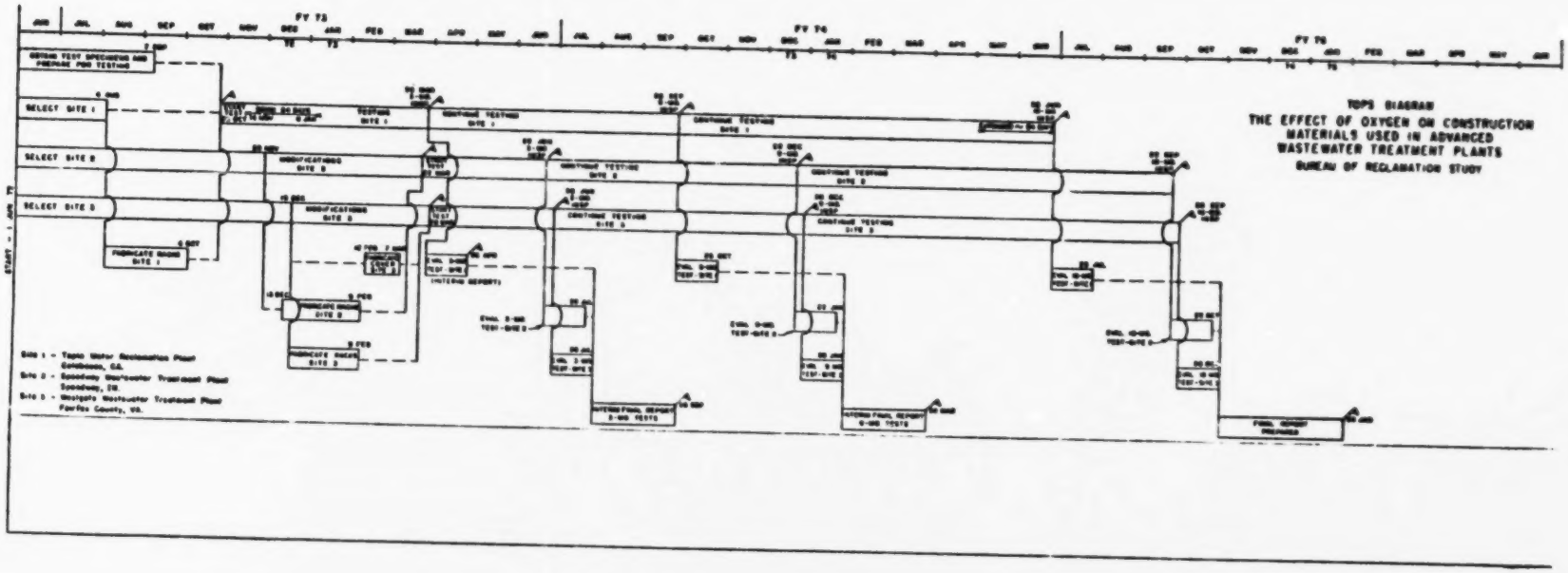
Vinyl resin, coal tar, coal-tar epoxy, Butyl, Urethane, Phenolic, Anodired, galvanized zinc.

Joint Sealers

Silicone, Urethane, Polysulfide.

APPENDIX

TOPS Diagram


TOPS DIAGRAM
THE EFFECT OF OXYGEN ON CONSTRUCTION MATERIALS USED IN ADVANCED WASTEWATER TREATMENT PLANTS
BUREAU OF RECLAMATION STUDY
FY 73
FY 74
FY 75
SELECT SITE 1
SELECT SITE 2
SELECT SITE 3
FABRICATE SKIDS SITE 3
Site 1 - Tapia Water Reclamation Plant Corcoran, CA.
Site 2 - Speedway Wastewater Treatment Plant Speedway, IN.
Site 3 - Westgate Wastewater Treatment Plant Fairfax County, VA.

CONCRETE

Typical Mix Data

	Type II and polymer impregnated	Type V
Cement, Laboratory No.	M-6400	M-5207
Aggregate source	Clear Creek*	Clear Creek*
Cement content, # cement/yd^3 concrete	549	525
Sand content, % by vol. of aggregate	42	42
Water cement ratio	0.51	0.51
Slump, in.	3.0	3.3
Entrained air, %	5.6	6.0

Aggregate Gradation

Sand		Coarse Aggregate	
Gradation	% retained	Gradation	% retained
Pan	5	#4-3/8"	40
#100	16		
# 50	24	3/8"-3/4"	60
# 30	25		100
# 16	15		
# 8	15		
	100		

Type II and Type V portland cement concrete specimens were cured for 14 days at 73.4° F and 100 percent relative humidity. The specimens were then stored at 73.4° F and 50 percent relative humidity until shipped to the test site for exposure.

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*A local aggregate deposit used in Bureau of Reclamation concrete testing programs.

Impregnation Procedure

Specimens prepared for impregnation were treated as follows:

1. Cure a. Prisms - 14 days at 100% RH, 73.4° F
   b. Cylinders - 10 days at 100% RH, 73.4° F

2. Dried in oven at 325° F for 24 to 72 hours

3. Cooled to room temperature for 24 hours

4. Weighed to nearest 0.1 gram

5. Specimens impregnated

   a. Vacuum of 1 atmosphere applied to impregnator for period 1/2 hour
   b. Impregnant, methyl methacrylate (MMA) monomer catalized with α, θ, butylazo isobutyronitrile, (Pennwalt Corporation, Lucidol Chemicals Division D-A79), stirred for 1/2 hour
   c. Impregnant introduced into impregnator while vacuum was being maintained
   d. Vacuum released from impregnator, and 40 psig pressure applied using compressed air

e. Pressure soaked in catalyzed monomer for 1 to 1-1/2 hours

f. Pressure reduced to atmospheric

6. Polymerization of catalyzed monomer impregnated specimens was accomplished by wrapping in foil and heating in oven to 167° F for a period of 16 hours and allowed to cool to room temperature.

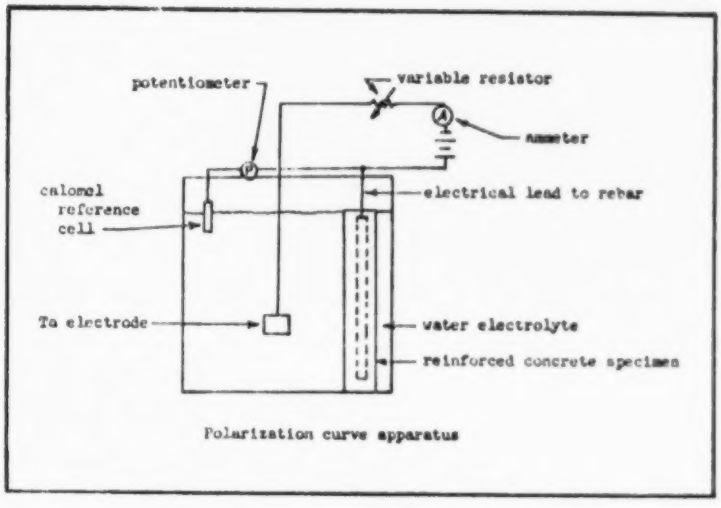
7. Specimens weighed to nearest 0.1 gram

Percent loading was calculated from the impregnated and dry weights.

STEEL REINFORCEMENT IN CONCRETE

Polarization Break Method of Determining Corrosion Rates of Steel Reinforcement Embedded in Concrete

Sketch of test schematic is shown below.



Polarization curve apparatus

Current is slowly increased by decreasing the resistance (variable resistor) until the impressed current is sufficient to overcome the anodic corrosion current. This point is determined by plotting the steel to electrolyte potential versus the log of the impressed current (E log I curve). The anodic current is the current at the break in the E log I curve. Similarly the cathodic corrosion current is

determined by reversing the polarity of the cell. The corrosion current is then computed from the formula below:

$$I = \frac{Ia\ Ic}{Ia + Ic}$$

where I is the corrosion current
Ia is the anodic current
Ic is the cathodic current

The corrosion rate is then computed as follows:

$$W = F \times I \times t$$

where W is the weight loss due to corrosion
F is Faraday's Number (20#/ampere-year for steel)
t is time

METALS AND ALLOYS

Corrosion coupons for the stressed and unstressed corrosion tests were procured from Corrosion Test Supplies Company, Baker, Lousiana. Data contained on certificates submitted are shown in Table 1.

The circular unstressed and rectangular stressed corrosion specimens were prepared for exposure as follows:

1. Degreased in hot vapor degreaser using perchloroethylene solvent
2. Washed with grit soap until free of water breaks
3. Sensitized specimens (304 and 316 SS only) were then heated to 1,200° F for 1 hour and cooled slowly
4. Circular coupons weighed to nearest 0.1 milligram
5. Mount circular coupons on corrosion test spools
6. Stress rectangular specimens (bend over 1-inch mandrel) and mount on coatings test spool

Cleaning procedure following exposure was accomplished as follows:

1. Photograph
2. Wash carefully to remove all soluble material with soap

3. Chemical cleaning of respective specimens as shown below:

Stainless steels: washing with soap using a stiff-bristle brush and rubber stopper.

Cast iron, mild steel, low alloy steel, and austinitic cast iron: immersion in hot caustic solution (20 percent sodium hydroxide with 200 grams of zinc dust added per liter), followed by washing with soap using a stiff-bristle brush and rubber stopper.

Copper: immersion in 18 percent hydrochloric acid solution, followed by washing with soap using stiff-bristle brush and rubber stopper.

Aluminum: immersion in 70 percent nitric acid solution followed by washing with soap using stiff-bristle brush and rubber stopper.

4. Drying and weighing to nearest 0.1 milligram

Corrosion rate was calculated using the following formula:

$$\text{Corrosion rate} = \frac{(WL)x(534)}{(D)x(A)x(T)}$$

where

Corrosion rate is in mils per year

D is the metal density in grams/cubic centimeter

A is the surface area of the coupon in square inches

T is the exposure time in hours, and

WL is the weight loss in milligrams

RUBBER AND PLASTIC MATERIALS
Proprietary Identification

Rubber Sheeting

R-5	Neoprene - Gaco Western Inc.
R-8	EPDM - Carlisle Tire and Rubber Company
R-17	Butyl - Carlisle Tire and Rubber Company
R-18	CSPE - Gaco Western Inc.
R-25	Natural - Goodyear Tire and Rubber Company
R-27	Polyacrylate - Thiokol Chemical Corporation
R-29	Butyl - Gates Rubber Company
R-30	EPDM - Gates Rubber Company
R-31	Butyl-EPDM blend - Presstite Division, Interchemical Corporation
R-32	Silicone - Dow Corning Corporation
R-34	Nitrile Butadiene - B. F. Goodrich Chemical Company
R-532	Silicone - General Electric Company

Plastic Sheeting

B-6273	CSPE - Reeves Brothers Inc.
B-6475	CPE - Goodyear Tire and Rubber Company
B-6514	PVC - Pantasote Plastics Company

Fabric Reinforced Flexible Sheeting

B-6386	Nylon reinforced CSPE - Burke Rubber Company
B-6399	Nylon reinforced EPDM - Firestone Coated Fabrics Company
B-6464	Nylon reinforced Butyl - Plymouth Rubber Company Inc.
B-6467	Nylon reinforced CPE - Snyder Manufacturing Company
B-6468	Nylon reinforced CPE - Snyder Manufacturing Company

Rigid Polymers

RS-1	Epoxy-fiberglass - Shell Chemical Company
RS-2	Polyester-fiberglass - Atlas Chemical Industries, Inc.
RS-3	Vinyl-fiberglass - Dow Chemical Company
RS-4	Hard rubber (Ebonite) - Gaco Western Inc.
RS-5	RPM pipe - Johns-Manville Corporation
RS-7	HDPE - Hancor, Incorporated

PROTECTIVE COATINGS

1. Phenolic - Carboline, St. Louis, Missouri

   Steel panels only

   primer - Carbo Zinc 11, inorganic zinc, thinned by addition of 1 pint of thinner (2:1 mixture of xylol and MEK) per gallon of primer

   topcoats - two coats Phenoline 368WG winter grade, modified phenolic

   applied by brushing in accordance with manufacturer's instructions

   dry-film thickness - 20 mils

2. Urethane - Carboline, St. Louis, Missouri

   Concrete panels only

   primer - Carboline 1320

   topcoat - Carboline x 1304-146, modified urethane, thinned by addition of 1 pint of thinner (1:1 mixture of xylol and MEK) per gallon of paint

   applied by brushing in accordance with manufacturer's instructions

   dry-film thickness - 20 mils

3 & 4. Vinyl - Amercoat 33, Ameron, Brea, California

Steel and concrete panels

USBR VR-3 system

four coats, first coat on concrete thinned by addition of one part vinyl thinner per one part of paint

applied by brushing

dry-film thickness - 6 mils

5. Vinyl - Amercoat 23, Ameron, Brea, California

Steel panels only

USBR VR-6 system

primer, three body coats and two seal coats

applied by brushing

dry-film thickness - 10 mils

6 & 7. Coal-tar epoxy - Porter Tarset, Louisville, Kentucky

Steel and concrete panels

conforms to MIL-P-23236, Type I, Class II

three coats to 20 mils

first coat on concrete thinned 50 percent with xylene

applied by brushing

8 & 9. Coal-tar enamel

Steel and concrete panels

one coat to 3/32 inch

primed with Type B (synthetic) primer

applied by dipping

10 & 11. Butyl - U.S. Polymeric, Santa Ana, California

Steel and concrete panels

primer - PC-8152

topcoat - PC-8152 two component butyl

thickness - two topcoats to 15 mils

applied by brushing in accordance with manufacturer's instructions

12 & 13. Butyl - Enjay, Houston, Texas

Steel and concrete panels

primer - none

topcoat - 6120 - two component butyl

thickness - two coats to 18 mils

applied by brushing in accordance with manufacturer's instructions

Zinc coating on racks

hot-dip zinc galvanized in accordance with ASTM: A 123 (2 ounces)

JOINT SEALERS

Code	Generic type	Manufacturer	Product	Primer
S-1	Silicone	General Electric	GE-1600	None
S-2	Urethane	Products Research Co.	PRC-270	#4
S-3	Polysulfide	W. R. Grace	HornflexL	2C

Joint sealers were mixed and applied in accordance with the manufacturer's instructions.

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